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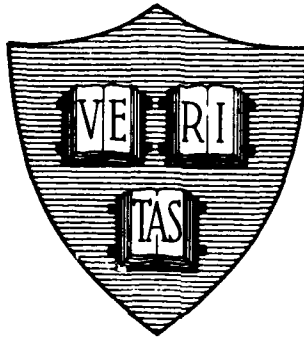
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INTRODUCTION

This report covers progress made during the past year in the work of eleven Research Units funded under the Joint Services Electronics Program at Harvard University. It is broken down into four major divisions of electronic research: *Solid state electronics*, *Quantum electronics*, *Information electronics*, and *Electromagnetic phenomena*. Following the report of the work of each Unit, there is a complete annual report of the associated Publications/Patents/Presentations/Honors. This report also includes a section on *Significant Accomplishments* which contains selected highlights from two of these areas. These are "Multiphoton Vibrational Excitation of Molecules" by Research Unit 8 and "Sensors for Pulses and for Detecting Submarines" by Research Unit 11.

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I. SOLID STATE ELECTRONICS

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I.1 Electronic Theory of Semiconductor Alloys and Superlattices. H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

During the past year the efforts of the group have been concentrated mainly on the electronic and optical properties of superlattices and the electronic and magnetic properties of diluted magnetic semiconductors.

A. Superlattices

Superlattices have been shown to be essential for optoelectronic applications. They may also be of importance to infrared detector technology. Finally, their study may be regarded as a precursor in the science of quantum dots and other types of recently MBE-fabricated man-made structures. The work of Ehrenreich's group specifically has been concerned with three projects: (1) Demonstration that $\mathbf{k} \cdot \mathbf{p}$ perturbation theory can be used as a predictive approach for describing effective masses and optical properties of superlattices. (2) The suggestion and theoretical investigation of charge activated light modulation (CALM) which has potential importance in optical systems

processing. The device we have suggested (in collaboration with R.V. Jones of Harvard) is based on intersubband transitions between the two lowest conduction bands of III-V superlattices. These same transitions have been proposed by researchers at AT&T Bell Labs as the basis of a new far-IR detector technology which may possibly be superior to the commonly used HgCdTe II-VI alloy system. (3) Resolution of the band offset controversy in HgTe/CdTe superlattices which has been a controversial issue in the field for sometime. A brief account of these accomplishments follows.

The $\mathbf{k} \cdot \mathbf{p}$ calculations question has relied on the use of the Kane model for both III-V and II-VI superlattices. In order to investigate whether the limited number of bands involved in that model is adequate for quantitative prediction, we have made a detailed comparison of our results with those of more elaborate $\mathbf{k} \cdot \mathbf{p}$ calculations developed by T.C. McGill's group at Caltech [1]. The computer code developed at Caltech takes into account many more basis states than the set considered in our calculations and uses different pseudo-wave functions in layers having different compositions. This comparison was made possible through a collaboration of G.Y. Wu, a former graduate student of McGill, who was a post-doctoral fellow associated with this group during the past year. Our results, which have now been submitted for publication in *Physical Review* [1], indicate that the limited number of bands considered in the model used here, which is a generalization of that originally developed by Kane for bulk band structures, is adequate for the calculations of optical properties and effective masses.

The same technique is being extended to include the d bands that are present in diluted magnetic semiconductors. The theory for bulk band structures, including spin polarization, has now been developed. Results concerning the valence band spin-orbit splitting dependence on Mn concentration have been obtained and compared with the experiments. These results are begin readied for publication. A new graduate student plans to investigate the effects of magnetic disorder utilizing the coherent potential approximation. Preliminary investigations concerning the generalization of

the superlattice treatment of III-V and II-VI compounds to DMS superlattices are also in progress. It appears that for nonmagnetic applications the infrared properties of DMS of importance to IR detectors possess no particular advantage over MCT. However continued investigations of II-VI alloys and superlattices is of importance because of potential applications of blue-green lasers and detectors for optical storage. (There are no III-V alloys having the requisite properties.)

Recent reports have highlighted the potential importance of intersubband transitions between the two lowest conduction subbands (C1, C2) of a semiconductor superlattice in optoelectronic applications. The absorption coefficient and change in refractive index associated with these transitions depends directly on the number of electrons in the lower subband and may be adjusted to exceed the values associated with the fundamental absorption of direct gap bulk semiconductors. The carrier dependence of the intersubband optical properties is the basis of a novel class of charge activated light modulators. A light beam tuned to the miniband gap energy propagates through an undoped superlattice without appreciable attenuation since there are no carriers in the C1 subband. If, however, the beam is polarized perpendicular to the superlattice planes and electrons are electrically injected into or optically generated within the superlattice, the beam can be modulated by the induced intersubband absorptive and/or refractive effects. One particularly promising configuration, which would be useful in communications and computer applications, is that of a crossed wave guide switch wherein cross channel coupling is controlled by carrier activated index changes at the intersection of the wave guides.

These applications are firmly based on the theoretical envelope function description of superlattices which has previously yielded quantitative results for effective masses and the optical properties in both III-V and II-VI superlattices. These results, obtained in collaboration with R.V. Jones of Harvard University, are described in a recent *Applied Physics Letter* [2]. Possible applications are being studied in detail by

Jones, although there are no plans to fabricate actual devices at Harvard because of the absence of the requisite equipment.

The dilemma posed by the differing valence band offsets Δ in HgTe/CdTe superlattices obtained from room temperature photoemission ($\Delta \approx 350$ meV) and low temperature magneto-optical experiments ($\Delta \approx 40$ meV) can be resolved in favor of the larger Δ by showing, as we have done, that the effective mass and the band gap obtained in the magneto-optical experiments are consistent with the larger value of the valence band offset. As noted previously, the conduction and valence bands of the semiconducting superlattices cross as the offset is increased from small values and render the material semimetallic. What has been missed is the fact that the superlattice again becomes semiconducting as the offset is increased further for the layer widths studied in the magneto-optical experiments. This resolution of the dilemma is appealing because it recognizes that both sets of experimental results are consistent with each other and simply notes that there has been oversight on the part of theorists in failing to recognize that after the semimetallic regime superlattice band structure becomes once again semiconducting with a band gap at the superlattice Brillouin zone face. These conclusions are based on the $\mathbf{k} \cdot \mathbf{p}$ perturbation theory that has been successfully used in explaining other superlattice properties and which we have every reason to think applicable to the present case as well. These results have been submitted to *Phys. Rev. Letters* for publication [3].

References:

1. N.F. Johnson, H. Ehrenreich, G.Y. Wu and T.C. McGill, "Superlattice $\mathbf{k} \cdot \mathbf{p}$ Models for Calculating Electronic Structure", *Phys. Rev. B*, (submitted for publication).
2. N.F. Johnson, H. Ehrenreich and R.V. Jones, "Carrier-Activated Light Modulation", *Appl. Phys. Lett.* 53(3), 180 (1988).

3. N.F. Johnson, P.M. Hui and H. Ehrenreich, "Valence Band Offset Controversy in HgTe/CdTe Superlattices: A Possible Resolution", *Phys. Rev. Lett.* (submitted for publication).

B. Magnetic Properties of Diluted Magnetic Semiconductors

The investigations of magnetic disorder in DMS have led to an empirically based and internally consistent picture of the electronic structure of these materials. This picture is consistent with the existing experimental information, and, to the best of our knowledge, inconsistent with none. This picture has been used to describe the magnetic interactions in the Mn-alloyed II-VI DMS on a microscopic basis. It has been possible to develop a description of the electronic and magnetic interactions on energy scales ranging from 10^{-5} eV to 10 eV.

We have considered compounds of the form $(\text{II})_{1-x}\text{Mn}_x(\text{VI})$ for a variety of ingredients belonging to Groups II (Hg, Cd, Zn) and VI (Te, Se, S) of the periodic table.

We have examined both isotropic and anisotropic exchange for CdMnTe and related materials. In the case of the isotropic exchange these represent the most accurate available thus far for any magnetic insulator. The reason for this improvement is associated with better knowledge of the electronic structure for semiconductors and the utilization of the empirically determined Te p - Mn d exchange interactions.

During the past year we have completed a quantitative calculation of isotropic superexchange and an explanation of the spin resonance linewidth narrowing in diluted magnetic semiconductors. The Dzyaloshinski-Moriya anisotropic superexchange is the dominant mechanism determining the paramagnetic resonance (EPR) linewidth in Mn-based II-VI DMS such as $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$. The Anderson Hamiltonian which was applied in our previous study of isotropic superexchange has been generalized to include the anion spin-orbit coupling responsible for anisotropic superexchange. The EPR lineshape has been calculated using a moment expansion of the magnetic

response function to first order in inverse temperature together with a maximum entropy ansatz. The calculated infinite temperature linewidths are in good agreement with extrapolated experimental values obtained by Samarth and Furdyna. A novel fit of the theoretical temperature dependence to the experimental linewidth data provides the first empirical value for the anisotropic exchange constant. This value is in excellent agreement with that obtained by our theoretical calculation. The calculated chemical trends for the exchange constants for the selenides and sulfides yield the experimentally expected trends.

Preliminary reports of this work have been presented at recent international conferences on magnetism and semiconductors. A complete account of this work has been submitted by B.E. Larson and H. Ehrenreich to *Phys. Rev.* for publication [1].

References:

1. B.E. Larson and H. Ehrenreich, "Anisotropic Superexchange and Spin-Resonance Linewidth in Diluted Magnetic Semiconductors", *Phys. Rev. B* (submitted for publication).

ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

B. E. Larson and H. Ehrenreich, "Anisotropic Exchange and Spin-Resonance Linewidths in Diluted Magnetic Semiconductors," submitted to *Phys. Rev. B*. (Partially supported by N00014-86-K-0760)

N. F. Johnson, H. Ehrenreich, G. Y. Wu, and T. C. McGill, "Superlattice $k \cdot p$ Models for Calculating Electronic Structures," submitted to *Phys. Rev. B*. (Partially supported by N00014-86-K-0033 and N00014-86-K-0760)

N. F. Johnson, P. M. Hui, and H. Ehrenreich, "Valence Band Offset Controversy in HgTe/CdTe Superlattices: A Possible Resolution," *Phys. Rev. Lett.* (Partially supported by N00014-86-K-0033)

b. Papers Published in Refereed Journals

K. C. Hass and D. Vanderbilt, "Bond Relaxation in $Hg_{1-x}Cd_xTe$ and Related Alloys," *J. Vac. Sci. Technol. A* **5** (5), 3019-3023 (1987). (Partially supported by N00014-86-K-0033)

N. F. Johnson, H. Ehrenreich, K. C. Hass, and T. C. McGill, " f -Sum Rule and Effective Masses in Superlattices," *Phys. Rev. Letters* **59** (20), 2352-2355 (1987). (Partially supported by N00014-86-K-0033 and N00014-86-K-0760)

N. F. Johnson, H. Ehrenreich, and K. C. Hass, "Effective Masses and Optical Matrix Elements in Semiconductor Superlattices," *Superlattices and Microstructures* **3**, 559 (1987). (Partially supported by N00014-86-K-0033 and N00014-86-K-0760)

K. C. Hass and H. Ehrenreich, "Electronic and Magnetic Properties of II-VI Diluted Magnetic Semiconductors," *J. Cryst. Growth* **86**, 8-14 (1988). (Partially supported by N00014-86-K-0760)

B. E. Larson, K. C. Hass, H. Ehrenreich, and A. E. Carlsson, "Theory of Exchange Interactions and Chemical Trends in Diluted Magnetic Semiconductors," *Phys. Rev. B* **37** (8), 4137-4154 (1988). (Partially supported by N00014-86-K-0033 and N00014-86-K-0760)

N. F. Johnson, H. Ehrenreich, and R. V. Jones, "Carrier Activated Light Modulation," *Appl. Phys. Lett.* **53** (3), 180-181 (1988). (Partially supported by N00014-86-K-0760)

K. C. Hass and H. Ehrenreich, "Band Structures of Semimagnetic Compounds," *Acta Physica Polonica* 5f A73 (6), 933-941 (1988). (Partially supported by N00014-86-K-0760).

c. Books (and sections thereof) Submitted for Publication

Editor (with D. Turnbull), *Solid State Physics*, Vol. 42 (Academic Press, 1989).

d. Books (and sections thereof) Published

Editor (with D. Turnbull), *Solid State Physics*, Vol. 41 (Academic Press, 1988).

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

H. Ehrenreich, "Electronic Theory of II-VI and Related Semiconducting Materials and Structures," DARPA IR Focal Plane Array Materials and Processing Review, McLean, VA, April 5-6, 1988.

H. Ehrenreich, "Electronic and Magnetic Properties of Diluted Magnetic Semiconductors," DARPA/URI Consortium on Diluted Magnetic Semiconductors and Related Materials, Raleigh, NC, May 25-26, 1988.

i. Honors/Awards/Prizes

Physics of Materials and Devices, Symposium in Honor of the Sixtieth Birthdays of Professors Henry Ehrenreich and Michael Tinkham, Harvard University, May 14, 1988.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.

Mr. N. F. Johnson and Mr. P. M. Young

I.2 Pressure Dependence of Photo-Luminescence Excitation in GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Multi-Quantum Wells. J. H. Burnett, H. M. Cheong, and W. Paul, Contracts N00014-84-K-0465 and N00014-86-K-0744; Research Unit 2.

Multi-quantum wells and superlattices of group 3-group 5 compounds such as GaAs are important semiconductors having both great fundamental interest and device importance. We have chosen to study the pressure dependence of suitable optical spectra of such structures as a way to elucidate the fundamental mechanisms of quantized state formation and of tunneling between adjacent wells. The philosophy of this approach is that the pressure dependence of the band structures of both well and barrier are well-known, so that a pressure experiment can study the result of varying the band structures in a known way on a single structure.

The photoluminescence (PL) and photoluminescence excitation (PLE) spectra are chosen for study as a function of both temperature and pressure. Since the changes with these parameters of the band structures of the well (GaAs) and barrier ($\text{Al}_x\text{Ga}_{1-x}\text{As}$) layers are well-established, the experiments permit us to study the changes of the quantized electron and hole energies as a function of the band structures of the well and barrier layers. The actual structures studied, designed by us and fabricated in collaboration with Dr. Emil Koteles and Dr. Boris Elman of GTE Laboratories, consisted of pairs of wells of different degrees of coupling at atmospheric pressure.

For $x = 0.3$ (a conventional choice) and pressure (P) ≤ 40 kbar, the principal effect of pressure is to change the nature of the barrier, by altering the relative energies of the Γ and X minima. The coupling between wells through the barrier is expected to depend on the relative energies of Γ and X , especially in the range of pressure ($P > 10$ kbar) where the energy of the X minima is below that of Γ . Thus, we have paid special attention to the shifts with pressure of the quantized levels as a function of the relative energies of Γ and X in the range of pressure between 10 and 40 kbar.

In past reports we have described measurements on pairs of wells with wide barrier widths, such that there was very little coupling either at atmospheric or elevated pressure. More recently we have been investigating in great detail the changes in energy of the allowed transitions between quantized hole and electron states when the barrier widths are sufficiently narrow that coupling of the double wells is inevitable. We now give a summary report of our findings.

For a coupled double quantum well (CDQW) the electron, heavy-hole, and light-hole levels are split into doublets, and the size of the doublet splitting is a measure of the coupling between the wells. For a symmetrical CDQW the coupled electron and hole states must all be either symmetric or antisymmetric with respect to the center of the barrier. In this case transitions can only occur between electron and hole states of the same symmetry; i.e., transitions between symmetric and antisymmetric states are forbidden. The result of this is: (1) The lowest energy peak observed in PLE for our CDQW structures has an energy given by the GaAs band gap plus the electron and heavy-hole confinement energies minus the exciton binding energy. There is also a corresponding light-hole transition peak. (2) The difference in energy between this lowest energy peak and the next most energetic peak associated with a heavy-hole transition is the sum of the electron and heavy-hole doublet splitting energies.

The purely electronic components of the energies of (1) and (2) can be separated out if one knows the energy of one of the "forbidden" transitions. We obtain this by applying a small electric field to the sample which distorts the potential profile and breaks the symmetry of the system making the "forbidden" transitions allowed. As a result, from measurements of the PLE spectra as a function of pressure for strongly coupled CDQW's, we have obtained the electronic confinement energy (minus the exciton binding energy) and coupled electron doublet splitting (Δe) as a function of the band structure of the barriers.

In contrast to the behavior of the electronic confinement energy of uncoupled

200 Å well width quantum wells, which is unchanged within the uncertainty of the measurement from 0–34 kbar, the confinement energy of the strongly coupled CDQW measured is unchanged to 18 kbar but decreases roughly linearly with pressure from 18–31 kbar by 15–20 meV at 31 kbar. The results for weakly coupled CDQW's are qualitatively similar but with a smaller drop in confinement energy. We will concentrate here on the strongly coupled CDQW system. Measurements of the pressure dependence of Δe for the strongly coupled CLQW showed that Δe is unchanged within the uncertainty of the measurement for $P < 18$ kbar, but there is an abrupt drop of 2 meV near 18 kbar after which it remains approximately constant to 31 kbar.

To understand the behavior of the electron confinement energy and Δe vs. P we must consider the effect on the electron confinement energies and Δe of all parameters that change with pressure. 1) Due to the compressibility of GaAs and AlGaAs there is a $\sim 1\%$ decrease in well and barrier widths for $P = 0 - 30$ kbar. The effects of these decreasing widths on the electron levels tend to cancel and the overall change at 30 kbar of the electron confinement energy is estimated to be less than 1 meV. 2) GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ have slightly different gap pressure dependences with the result that the barrier height is slightly dependent on pressure, the direction depending sensitively on the value of x for x near 0.27. We estimate that a pressure dependent barrier height could shift the electron energy levels by no more than 2 meV and Δe no more than 1 meV but linearly. 3) In bulk GaAs the electron effective mass (m^*) is expected to increase nearly linearly with pressure by $\sim 20\%$ for $P = 30$ kbar. Since the electron confinement energy varies roughly as $1/m^*$ the effect of a pressure dependent m^* would be expected to decrease the confinement energy with pressure. An effective mass approximation calculation using an m^* derived from lowest order $\mathbf{k} \cdot \mathbf{p}$ theory, ignoring band mixing, predicts that the effect of a pressure dependent m^* would be to decrease the lowest electron level energy roughly linearly with pressure by 4 ± 0.5 meV for $P = 30$ kbar. Also, the exciton binding energy is dependent on

m^* , but we estimate this to affect the transition energies by less than 1 meV. The effect of a pressure dependent m^* on Δe , ignoring band mixing, is calculated to be a roughly linear decrease in Δe with pressure by 4 ± 1 meV for $P = 30$ kbar.

These three effects predict a roughly *linear* decrease in the lowest electron confinement energy with pressure by at most 7 meV for $P = 30$ kbar. However, our results show that the effect of pressure on the electron confinement energies is distinctly *non-linear* and results in a drop by 15–20 meV at 31 kbar. Also, these arguments predict that Δe should decrease roughly linearly by ~ 4 meV at ~ 30 kbar, in contrast to our finding of a smaller but very *nonlinear* decrease. Clearly these pressure-dependent parameters cannot explain our measurements.

We appeal to $\Gamma - X$ band mixing, which must occur to some extent, as a possible explanation. Strongly suggesting that $\Gamma - X$ mixing is related to our observed anomalies is the fact that the X band of the barriers becomes equal in energy to the highest $n = 1$ electron state at ~ 20 kbar, about the energy at which the electronic confinement energies and Δe begin to deviate from their atmospheric pressure values. The decrease, both with and without correction for a pressure dependent m^* , in the lowest electron state confinement energy for $P < 20$ kbar is consistent with the idea that $\Gamma - X$ mixing in the barrier region would allow the electron to tunnel more easily through the barrier and thus increase the coupling between the wells. The behavior of Δe is somewhat anomalous from this simple picture. Though there is a *net* increase in Δe for $P = 20 - 30$ kbar after correction for a pressure dependent m^* (consistent with this picture), the discontinuity at ~ 20 kbar is a decrease. However, the effect of band mixing on Δe is complicated by the fact that band mixing should affect m^* . A proper treatment of m^* must include this mixing, and this would affect the calculated energies of the electron states and also their exciton binding energies. Without yet having the proper calculation available to us, we can only predict that the onset of $\Gamma - X$ mixing should give rise to a change in Δe .

In summary, we have demonstrated that the coupled electron levels of CDQW's show anomalous behavior at and above the pressure region where the X band of the barriers crosses these levels. This behavior, which cannot be explained as resulting from a pressure dependent bulk m^* , suggests $\Gamma - X$ band mixing, but is not entirely consistent with a simple band mixing picture. It is hoped that a detailed study of the behavior of the electron level splittings in the cross over region for CDQW's of various barriers widths compared with more sophisticated $\Gamma - X$ band mixing models will give a better understanding of the $\Gamma - X$ in these materials.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

J. H. Burnett, H. M. Cheong, W. Paul, E. S. Koteles, and B. Elman, "Modification of the Coupling of Double Quantum Wells Through Band Structure Changes under Hydrostatic Pressure," to be published in the (refereed) Proceedings of the 4th International Conference on Superlattices, Microstructures, and Microdevices, Trieste, 1988.

b. Papers Published in Refereed Journals

J. R. Eggert and W. Paul, "Recombination in Disordered Semiconductors: The Nearest Available Neighbor Distribution," submitted to *Phys. Rev. B*.

Note: In addition, the group published six other papers on work supported primarily by other contracts, with subsidiary support from the JSEP.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.

Mr. J. H. Burnett, Mr. H. Cheong, and Ms. S. Lee.

I.3 Liquid Crystals and X-Ray Surface Characterization I. Tidswell, T. Rabedeau and P.S. Pershan, Contracts N00014-84-K-0465, NSF DMR-85-13523, and NSF DMR-86-14003; Research Unit 3.

In view of the fact that the X-ray synchrotron at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratories (BNL) was not operational, most of our progress this past year was confined to analysis of previous measurements and preparations for new ones that will start as NSLS resumes operations in the fall of 1988.

We have refined our numerical methods for analyzing the surface reflectivity data on buried substrates and we are currently completing the draft of a manuscript on the X-ray reflectivity studies of the structure of monomolecular coatings of alkyl siloxanes on Si/SiO₂ surfaces [1]. This work is carried out in collaboration with Prof. George Whitesides of the Harvard Chemistry department and it receives joint support from the JSEP program and the Harvard Materials Research Laboratory.

In this report year we developed a Patterson function technique from which one obtains the absolute value of the correlation function:

$$\Xi(z) \equiv \int_{-\infty}^{\infty} dz' \frac{1}{\rho_{\infty}^2} \left(\frac{\partial \rho(z')}{\partial z'} \right) \left(\frac{\partial \rho(z' + z)}{\partial z'} \right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dQ |\Phi(Q)|^2 e^{-iQz} \quad (1)$$

where $\partial \rho(z)/\partial z$ is the derivative of the average of the electron density along the direction normal to the surface; $|\Phi(Q)|^2 \equiv R(Q)/R_F(Q)$ where $R(Q)$ is the measured reflectivity and $R_F(Q)$ is a theoretical reflectivity as a function of incident angle α , i.e. $Q = (4\pi/\lambda) \sin(\alpha)$ and λ is the X-ray wavelength. The largest term in $\partial \rho(z)/\partial z$ occurs at the interface between the solid and the vapor at $z \approx 0$ and since:

$$\int_{-\infty}^{\infty} dz \frac{1}{\rho_{\infty}} \left(\frac{\partial \rho(z)}{\partial z} \right) \approx 1 \quad (2)$$

one might approximate

$$\frac{\partial \rho(z)}{\partial z} \approx \delta(z) + \frac{\partial \delta \rho(z)}{\partial z} \quad (3)$$

where $\delta\rho(z)$ describes all variations in electron density except for the initial interface with the vapor. If the width of the interface is not too large and the second term is sufficiently small:

$$\Xi(z) \approx \frac{1}{\rho_{\infty}} \left(\frac{\partial\rho(z)}{\partial z} \right) + \frac{1}{\rho_{\infty}} \left(\frac{\partial\rho(-z)}{\partial z} \right) . \quad (4)$$

Although the result in Eq. (4) is only approximate it illustrates the fact that the function $\Xi(z)$ gives direct information of the structure of the electron density near to the surface. It is especially important to notice that this information is not sensitive to assumptions about the phase of the X-ray scattering amplitude and it is not model dependent.

Previously we had been interpreting the measured $R(Q)$ by constructing model electron densities and then using nonlinear least square fitting procedures to find the model that would result in the best agreement between a calculated reflectivity and the measured values. While this type of procedure is extremely sensitive to very fine details, it is almost impossible to ever prove that the model is unique. In particular for the present problem of alkyl siloxanes on Si/SiO₂ surfaces, the modelling procedure strongly suggested the existence of an SiO₂ layer, approximately 20Å thick, separating the crystalline silicon and the alkyl siloxane. On the other hand, since the electron density difference between crystalline silicon and SiO₂ is only of the order of 5% it was difficult to determine whether the effects that were being attributed to this layer might not also be explained by some other subtle feature of the structure. In view of the fact that the distance between the Si/SiO₂ interface and the solid/air interface is much longer than any other length scale in the problem, the real space structure $\Xi(z)$ resolved any ambiguity in the modelling results.

The net result of a combination of the modelling and the Patterson function techniques was that we were able to show that the thickness of the SiO₂ layer is 21.4 ± 0.5 Å and that the mean square width of the Si/SiO₂ interface is less than approximately 2Å. This limit is primarily a result of the fact that since, with increasing

incident angles α the X-ray reflectivity usually falls at least as fast as $1/\alpha^4$, the reflected signal fell to approximately 1 count per second at values of $Q \approx 0.8 \text{ \AA}^{-1} \sim 0.9 \text{ \AA}^{-1}$ and this set a practical limit on the range of Q 's that could be studied. This is not a fundamental limit and selected future measurements will be made on synchrotron beam lines with one or more orders of magnitude of intensity. The practical resolution for the range of Q 's that were measured in these experiments corresponded to $\Delta z \approx \frac{1}{2}(\pi/0.9) \text{ \AA} = 1.7 \text{ \AA}$. In addition we demonstrated that there is structure within the SiO_2 /alkyl siloxane interface on approximately this same length scale. It appears that the mean square width of the interface between the alkyl region and the air is close to the mean square width of the bare SiO_2 /air interface prior to deposition of the alkyl siloxane monolayer.

Other results on the alkyl siloxane coated substrates will be described in full detail in the manuscript that will be completed within the next few weeks. For the purposes of the present project, we believe that the most significant progress has been the fact that within this past year we were able to establish an objective case that the technique of X-ray specular reflection is a viable tool for studying a wide variety of buried interfaces. A recent DOE study panel considered the range of possible technological applications for molecular monolayer film coatings on various solids and we believe that a second important result has been the relatively detailed characterization of the structure of one type of film [2]. Within the last few months we have used this case to persuade personnel at AT&T Bell Laboratories to develop a collaborative program to investigate buried interfaces of both Si/SiO_2 and Si/Ge under different growth conditions. These interfaces have important technological properties and we believe that the X-ray technique will allow us to obtain information that is not available by any other technique.

To this end we have carried out a number of digital simulations in order to demonstrate that the technique is theoretically capable of measuring certain features

of interest. In addition we have met with AT&T personnel to develop an experimental strategy and we have made preliminary designs for a portable UHV chamber that will allow transport of samples grown at AT&T to the synchrotron source. We expect that construction of the first prototype will begin in the next several weeks.

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2. Swalen, J.D., D.L. Allara, J.D. Andrade, E.A. Chandross, S. Garoff, J. Israelachvili, T.J. McCarthy, R. Murray, R.F. Pease, J.F. Rabolt, K.J. Wynne, and H. Yu, "Molecular Monolayers and Films," *Langmuir*, vol. 3, p. 932, 1987.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

Braslau, A., P.S. Pershan, G. Swislow, B.M. Ocko and J. Als-Nielsen, "Capillary waves on the surface of simple liquids measured by X-ray reflectivity," *Phys. Rev. A* (To be published, Sept., 1988).

c. Books (and sections thereof) Submitted for Publication

Pershan, P.S. "Scattering from Mesomorphic Structures" (to be published in the International Tables for Crystallography: Vol. B).

Pershan, P.S., "Structure of Liquid Crystal Phases" (to be published, World Scientific Publishing Co., Singapore, 1988).

Partial support provided by NSF Grants DMR-83-16979 and DMR-85-13523

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

P.S. Pershan, "X-ray Reflectivity as a Tool for Studying Liquid and Solid Surfaces," Winter Gordon Conference on Organic Thin Films," Oxnard, CA (Jan., 1988).

P.S. Pershan, "Liquid and Solid Surfaces," Second Users Meeting for the Advanced Photon Source, Argonne National Laboratory, March, 1988.

P.S. Pershan, "Liquid and Solid Surfaces," Plenary Lecture at the User's Meeting for the Advanced Photon Light Source, Argonne National Laboratory, March, 1988.

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

Tidswell, I.M., S.R. Wasserman, B.M. Ocko, and P.S. Pershan, "X-ray Grazing Incidence Reflectivity Studies of Silane Coated Polished Silicon," *Bul. Am. Phys. Soc.*, vol. 32, p. 452 (1987). (Partial support NSF Grants DMR-83-16979 and DMR-85-13523)

Amador, S., and P.S. Pershan, "Light-Scattering Study of the Smectic C to Smectic A Transition in Thin, Freely Suspended Liquid Crystal Films," *Bul. Am. Phys. Soc.*, vol. 32, p. 474 (1987). (Partial support NSF Grants DMR-83-16979 and DMR-85-13523)

j. **Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.**

Ian Tidswell, Graduate Student, 9/1/87 through 8/31/88

Tom Rabedeau, Post Doctoral Research Fellow, half time, 6/1/88 through 8/31/88

I.4 High Temperature Superconductivity. G. Spalding, L. Ji, C. J. Lobb, and M. Tinkham Contract N00014-84-K-0465, and NSF Grant DMR-86-14003; Research Unit 4.

We have made significant progress in three areas: phenomenology of the resistive transition, tunneling studies of the Bi compound, and harmonic generation in YBCO. These are described briefly below:

a) *Resistive transition:* In 1987, Müller, Takashige, and Bednorz [1] demonstrated the existence of an "irreversibility line" in high temperature superconductors which separates the region of reversible magnetization near T_c from the irreversible region in which measurable (and useful) persistent irreversible supercurrents can exist. The form of this line was found to be

$$1 - t \propto H^{2/3}$$

where $t = T/T_c$. They interpreted this result in terms of a spin-glass analogy, but in 1988 Yeshurun and Malozemoff [2] proposed an attractive alternative interpretation in terms of more conventional thermally-activated flux creep ideas. In their model, they introduce a field-dependent activation energy $U_0 \propto H_c^2 \xi / B \propto (1 - t)^{3/2} / B$, and interpret the irreversibility line as the condition for this U_0 to be so large compared to kT that nonequilibrium currents decay sufficiently slowly to give apparently persistent currents.

In our work [3], we have extended this model to the regime where U_0/kT is not so large. In that case, instead of persistent currents, there is measurable resistance because of flux motion. We argue that the resistance should follow the form derived in 1969 by Ambegaokar and Halperin [4] for the resistive transition in a heavily-damped Josephson junction. In this way, we are able to give a natural explanation of:

- 1) the fact that the resistive transition of high- T superconductors gets increasingly broad in the presence of magnetic flux (in fact, $\Delta T \propto B^{2/3}$);

- 2) the fact that the resistively determined upper critical field $H_{c2}(T)$ appears to vary as $(1 - t)^{3/2}$ rather than the expected $(1 - t)$, and also that it greatly underestimates the true thermodynamic H_{c2} ;
- 3) the actual shape of $R(T; H)$ and its dependence on the quality of the material as measured by $J_{co}(0)$.

From these successes of the model, we also extrapolate that it will be hard to avoid the existence of appreciable resistance in these materials at high temperatures. That is, even if a material could be found with T_c as high as 400 K, well above room temperature, it might be expected to show resistance at room temperature if used in the presence of substantial magnetic fields (as in magnets, levitation systems, motor/generators, etc.) Of course, further work will be required to test the generality of our conclusion, but, if generally valid, it does pose a serious restriction on the range of applications that will be open for high temperature superconductivity.

In addition to the analytical work described above, we have also written a more general review [5] of the physical properties of the new superconductors for publication as a chapter in the *Solid State Physics* series, edited by Ehrenreich and Turnbull. The number of preprint requests received for this paper exceeds by two orders of magnitude that for any other paper I have written in 30 years!

b) *Tunneling in the Bi superconductor:* Point-contact tunneling experiments on the high- T_c bismuth compound have been carried out by graduate student G. Spalding using etched Nb and NbTi points. The samples were single crystals kindly supplied by Dr. D. E. Morris of LBL, Berkeley. These experiments were performed in a rig used earlier for studies on conventional superconductors, which permits adjusting the point contact while the sample is at low temperatures. This is important because repeated contacts must be made in order to identify typical behavior from the range of I-V curves obtained in successive penetrations of the insulating surface oxide barrier.

Examination of the surface by scanning electron microscope before and after contact shows that the point makes a "furrow" in the originally smooth surface layer because of lateral motion induced the act of applying sufficient contact pressure to make usable electrical contact. Thus, we believe our data are representative to bulk, not surface, properties of the material. Although the analysis of our results is still in a preliminary stage, it appears that these materials show an energy gap with a width such that the ratio $2\Delta/kT_c$ is comparable with the BCS value of 3.5, *i.e.* with $V_g \approx 22$ meV, a value far above that found in any of the classic superconductors.

c) *Harmonic generation experiments:* Measurements of the nonlinear electromagnetic response of YBCO samples have been carried out by graduate student Li Ji using a mutual inductance apparatus with its output coupled into a spectrum analyzer. In the absence of a dc magnetic field, one observes only the odd harmonics; in the presence of a dc field, the even harmonics become strong enough to measure. The fall-off in amplitude of the harmonics is found to be fairly well described by the predictions of the macroscopic Bean model [6] of flux penetration into superconductors with a given critical level of irreversible current density, but a more microscopic model in terms of "intergranular" Josephson weak links may be required to explain all the observations. Such a model has, in fact, been proposed recently by Jeffries *et al.* to explain similar data [7].

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I.5 Quantum Phenomena in Mesoscopic Josephson Junctions. M. Iansiti, A.T. Johnson, and M. Tinkham. Contracts N00014-83-K-0383 and N00014-84-K-0465, and NSF Grant DMR 84-04489; Research Unit 4.

With the publication of a second Physical Review Letter [1], submission of a comprehensive article to Physical Review [2], and submission of a Ph.D. thesis by M. Iansiti, the first generation of our experimental and theoretical investigations of the physical phenomena observed in very small superconducting tunnel junctions is nearing its successful completion. These so-called mesoscopic junctions have areas of about 10^{-9}cm^2 , i.e., about 1000 atoms on a side, so that their size is large on the atomic scale but small on the macroscopic scale. Junctions of this size have capacitances as small as 1 fF, so that the charging energy $e^2/2C$ of a single electron is of order 1 Kelvin in temperature units; this is large enough to give readily observable effects in superconducting or normal state tunnel junctions at helium temperatures and below.

In work reported previously, we had demonstrated the transition from the semi-classical regime of Josephson junctions, in which the phase difference variable ϕ could be treated as a number, to the quantum regime, in which the quantum fluctuations of ϕ were comparable with 2π . In the latter regime, the critical current was shown to be proportional to $1/R_n^2$ rather than the usual $1/R_n$ of the classical regime, and a reasonably quantitative account was given for the existence and magnitude of the resistance R_0 of the junction even below its critical current.

In the past year, we have studied the even more extreme quantum regime, obtained by application of a magnetic field, in which the charging energy *greatly* exceeds the Josephson energy. In this case, the charge variable is almost classically well defined, and the phase almost entirely washed out by the effect of the quantum fluctuations.

In this regime, we obtain I-V curves which show a remarkable coexistence of the "Coulomb blockade" associated with single electron tunneling, together with a finite "critical supercurrent," albeit one that occurs at a substantial voltage level ($\sim e/2C$) associated with the blockade. At present there is no available theory that can account in any detail for our observations, which are quite unexpected. However, we have developed phenomenological models which can account for most of the features. Because these phenomena are sensitive to the charging energy associated with a single net electronic charge on the electrodes, they have potential applications for very sensitive electronic devices. In the next year, we hope to explore some new configurations with this potential application in mind.

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2. M. Iansiti, A. J. Johnson, W.F. Smith, C.J. Lobb, and M. Tinkham, *Phys. Rev. B*, submitted.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

M. Tinkham, "The Resistive Transition of High Temperature Superconductors," *Phys. Rev. Lett.*, submitted. (Partial support also from NSF DMR-84-04489, MRL grant DMR-86-14003, and ONR N00014-83-K-0383.)

M. Iansiti, M. Tinkham, A.T. Johnson, W.F. Smith, and C.J. Lobb, "Effect of Charging Energy on Small Superconducting Tunnel Junctions," *Phys. Rev. B*, submitted. (Partial support also from NSF DMR-84-04489 and ONR N00014-83-K-0383.)

b. Papers Published in Refereed Journals

M. Iansiti, A.T. Johnson, C.J. Lobb, and M. Tinkham, "Crossover from Josephson Tunneling to the Coulomb Blockade in Small Tunnel Junctions," *Phys. Rev. Lett.* **60**, 2414-2417 (1988). (Partial support also from NSF DMR-84-04489 and ONR N00014-83-K-0383.)

c. Books (and sections thereof) Submitted for Publication

M. Tinkham and C.J. Lobb, "Physical Properties of the New Superconductors," to appear as chapter in *Solid State Physics*, Vol. 42, published by Academic Press. (Partial support also from NSF DMR-84-04489 and ONR N00014-83-K-0383.)

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

M. Tinkham, "Quantum Properties of Very Small Josephson Junctions," Conf. on Quantum Coherence, Univ. Of Minnesota, October, 1987.

M. Tinkham, "Overview of the High Temperature Superconductors," RF EXPO East, Boston, November, 1987.

M. Tinkham, "Charging Energy and Quantum Phase Delocalization in Small Josephson Junctions" and "Two Dimensional Superconducting Arrays and Granular Superconductors," Latin-American Conference on High Temperature Superconductivity, Rio de Janeiro, May, 1988. (Travel expenses paid by Brazilian sources.)

M. Tinkham, "Superconductivity: Past, Present, and Future," IEEE meeting, Boston, May, 1988.

M. Tinkham, "The Resistive Transition in High Temperature Superconductors," Workshop on Superconducting Phenomenology, Los Alamos, September, 1988.

i. **Honors/Awards/Prizes**

Physics of Materials and Devices, Symposium in Honor of the Sixtieth Birthdays of Professors Henry Ehrenreich and Michael Tinkham, Harvard University, May 14, 1988.

j. **Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.**

Dr. Mark Rzchowski and Mr. S.P. Benz. (Note: Five other students share JSEP facilities, but have no JSEP salary.)

I.6 Nonlinear Dynamics of Electronic Neural Networks. K. L. Babcock, C. Marcus, and R. M. Westervelt, Contract N00014-84-K-0465; Research Unit 5.

Electronic neural networks are complicated nonlinear dynamical systems which can exhibit complex behavior in addition to their desired functions. In the past year we have investigated issues which are relevant to the stability and proper functioning of neural networks implemented as integrated circuits. These include the shapes of the basins of attraction [1] and the stability [2,3] of Hopfield networks composed of realistic neurons with time delay, as well as the hysteretic dynamics of spin systems [4].

Our work on basins of attraction [1] was primarily done on an analog network composed of op-amp neurons with adjustable time delays obtained using charge-coupled delay devices. The basins of attraction for different stored and spontaneously-occurring steady states were measured by repetitively loading initial conditions which were raster scanned across a two-dimensional slice of the space of initial conditions. The final state reached after the network relaxed was shown on a storage display. This apparatus is orders of magnitude faster than digital simulations of this problem, demonstrating the inherent speed advantage of analog neural networks. Partly for this reason, relatively little information about the shapes of basins of attraction has been reported, other than estimates of their volume. Digital simulations of the same networks were used to check the results.

Using this apparatus we investigated [1] the influence of overcrowding (too many stored memories) and time delay on the basins of attraction. With a negligible neuron delay and a small number of stored memories, the basins were smooth, convex, and of comparable size, as desired. However, when too many memories were stored, the basins developed complex shapes with irregular sizes even without added time delay, so that many initial conditions relaxed to distant stored memories which were not the closest approximation. As time delay was added, the system developed a sustained

collective oscillation involving many neurons. The size of the basin of attraction for this oscillatory state increased in size with delay to take over a large proportion of the space of initial conditions. Such oscillatory states are clearly undesirable in practical networks.

Guided by results on our analog network, we conducted a systematic analysis of the stability of neural network with time delay [2,3]. By investigating the stability of different interconnection topologies for symmetric Hopfield networks with delay we were able to obtain criteria [2,3] for the design of stable networks. Paradoxically we found that loops tend to be stable, but that maximally interconnected networks in which each neuron is connected to every other (this topology is called a "clique" in graph theory) tend to be unstable when the interconnections are "frustrated", i.e., present conflicting inputs to the neurons. This frustration is the fundamental condition which allows networks to store more than one memory. The most unstable configuration is a totally frustrated clique, an example of which is the "winner take all" circuit used for optimization problems. Using analysis and measurements on our network we obtained a stability criterion [3] for totally frustrated cliques, which can be stated approximately in the following simple form. A totally frustrated network with N neurons with identical RC times will be free of oscillatory steady states if

$$RC > (2/\pi)(N^2 - 2N)\tau_{\text{delay}} \quad ,$$

where τ_{delay} is the neuron delay time. This relation is a consequence of two simple conditions: the relaxation time for the network as a whole is RC/N , and the gain of each neuron must be $A < N$ in order to store memories. This stability criterion places severe constraints on the size of real networks. For example, if $\tau_{\text{delay}} = 100$ nsec and $N = 1000$, the relaxation time for the network as a whole must be $RC/N > 60$ μ sec, and for each interconnection $RC > 60$ msec. We have shown [3] that these constraints can be eased considerably by randomly cutting a small fraction of the interconnections to create loops. We have also investigated the stability of a commonly used type of

Hopfield network which uses the Hebb rule to store memories [3]. In the case where the resistors of the interconnection matrix can have any value, the network is stable for an arbitrarily long neuron time delay. However, for the case of a "clipped" interconnection matrix, for which the resistor values lie within finite limits, the network can oscillate when the network relaxation time is shorter than the time delay.

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2. R. M. Westervelt and C. M. Marcus, "Stability of Neural Networks with Time Delay," presented at Conf. on Neural Networks for Computing, Snowbird, Utah, 1988.
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3. S. H. Strogatz, C. M. Marcus, R. M. Westervelt, and R. E. Mirollo, "Simple Model of Charge-Density Wave Dynamics with Phase Slippage," submitted to *Phys. Rev. Lett.*

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

S.H. Strogatz, C.M. Marcus, R.M. Westervelt, and R.E. Mirollo, "Solvable Model of Charge-Density Wave Dynamics with Phase Slippage," *Phys. Rev. Lett.*, submitted.

C. Marcus and R.M. Westervelt, "Stability of Analog Neural Networks with Delay," *Phys. Rev. A*, submitted.

b. Papers Published in Refereed Journals

K.L. Babcock and R.M. Westervelt, "Dynamics of Simple Electronic neural Networks," *Physica* **28D**, 305 (1987).

C.M. Marcus and R.M. Westervelt, "Basins of Attraction for Electronic Neural Networks," in *Neural Information Processing Systems, Denver, 1987* (Dana Z. Anderson, ed.) (American Institute of Physics, New York, 1988) p. 524.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

R.M. Westervelt, "Dynamics of High-Electric-Field Domains in Ge," Annual Meeting California Coordinating Committee for Nonlinear Studies, University of California Santa Cruz, March 25-26, 1988. (Partial support by ONR Contract N00014-84-K-0329).

R.M. Westervelt, "Stability of Neural Networks with Time Delay," Neural Networks for Computing, Snowbird, Utah, April 6-9, 1988.

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

C.M. Marcus and R.M. Westervelt, "Basins of Attraction for Electronic Neural Networks," in *Neural Information Processing Systems, Denver, November 8-12, 1987*.

C.M. Marcus and R.M. Westervelt, "Stability of Neural Networks with Time Delay," First Annual Meeting of the INNS, Boston, September 6-10, 1988.

i. Honors/Awards/Prizes

R.M. Westervelt — Cochairman of the 1988 Gordon Conference on Condensed Matter Physics.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.

Messrs. C.M. Marcus (Bell Scholar, no salary support), K.L. Babcock, and R. Seshadri (partial support).

II. QUANTUM ELECTRONICS

Personnel

Prof. N. Bloembergen
Assoc. Prof. E. Mazur
Dr. M. Buijs
Dr. Cheng-Zai Lu
Mr. K. H. Chen

Mr. D. S. Chung
Mr. P. Saeta
Mr. J. K. Wang
Mr. J. P. Wang

II.1 Picosecond Laser Interaction with Solid Surfaces M. Buijs, P. Saeta, E. Mazur, and N. Bloembergen, Contract N00014-84-K-0465; Research Unit 7.

To obtain more complete information on the electronic structure of the high-temperature phase of carbon, a new experimental arrangement has been implemented. As before, the sample is heated with a 20 ns pulse at 532 nm from a frequency-doubled Nd-Yag laser. An especially designed flashlamp has been constructed to obtain a high-temperature continuum probe pulse lasting about ten nanoseconds. This pulse is spectrally-dispersed and focused onto the slit of a Hamamatsu streak camera, which provides a temporal resolution of 1 ps, and a multi-channel analyzer detector. Thus, time-resolved reflectivity data over a wide spectral interval can be obtained from a single spot on the sample. The reflectivity will be measured for both *s*- and *p*-polarization over a wide range of angles of incidence. From such data the dielectric response function of the high-temperature phase of carbon can be determined. The operation of time-resolved reflectivity measurements with the streak camera have been tested successfully on silicon, and evidence for superheating in the molten silicon phase has been confirmed.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

- a. **Papers Submitted to Refereed Journals (and not yet published)**
N. Bloembergen, "Time Reversal and Spatial Inversion in Magneto-electric and Nonlinear Optical Phenomena," Proceedings of the Symposium on Space-Time Symmetries, *Nuclear Physics B*, Supplement 1988.
- b. **Papers Published in Refereed Journals**
N. Bloembergen, "A Quarter Century of Stimulated Raman Scattering, *Pure and Appl. Chem.* 59, 1229-1236 (1987).
N. Bloembergen, "Time Reversal and Spatial Inversion in Magneto-electric and Nonlinear Optical Phenomena," Proc. of the Symposium on Space-Time Symmetries, *Nuclear Physics B*, Supplement 1988.
- c. **Books (and sections thereof) Submitted for Publication**
J.-K. Wang, P. Saeta, M. Buijs, M. Malvezzi, and E. Mazur, "Single-shot Reflectivity Study of the Picosecond Melting of Silicon Using a Streak Camera," to appear in *Ultrafast Phenomena VI*, eds. C.B. Harris, T. Yajima and K. Yoshihara, Springer-Verlag, 1988.
- g. **Invited Presentations at Topical or Scientific/Technical Society Conferences**
N. Bloembergen, Invited Lecture at the Symposium on Space-Time Symmetries in Honor of Eugene Wigner, University of Maryland, May 24-28, 1988.
N. Bloembergen, "A Quarter Century of Nonlinear Optics," Keynote Address at the Topical Meeting on Nonlinear Optical Materials, Troy, New York, August 22-25, 1988.
- h. **Contributed Presentations at Topical or Scientific/Technical Society Conferences**
J.-K. Wang, P. Saeta, M. Buijs, M. Malvezzi, and E. Mazur, "Single-shot Reflectivity Study of the Picosecond Melting of Silicon Using a Streak Camera," Presented at the Sixth International Conference on Ultrafast Phenomena, Mt. Hiei, Japan, July 1988.
- i. **Honors/Awards/Prizes**
N. Bloembergen, Doctor of Science, Honorary, University of Connecticut, May 22, 1988.

II.2 Multiphoton Vibrational Excitation of Molecules. E. Mazur, J. Wang, and K. H. Chen, Contracts N00014-84-K-0465 and ARO DAAG29-85-K-0060; Research Unit 8.

In this research unit the dynamics of infrared multiphoton excited polyatomic molecules is studied by time-resolved spontaneous and coherent Raman scattering. During the past reporting period the first measurements with the new coherent anti-Stokes Raman spectroscopy (CARS) setup were carried out. One of the graduate students involved in this project, Mr. J. Wang, completed the work necessary for his Ph.D. thesis on the spontaneous Raman work. In addition, using computer modelling of the infrared multiphoton excitation we have succeeded in understanding the observed difference in behavior for the molecules studied in the spontaneous Raman experiment.

The CARS setup was synchronized with the CO₂ laser and the data acquisition system. The first series of preliminary measurements on various liquids and gases indicated that it was possible to measure CARS spectra at pressures as low as 1 Torr, with a time-resolution of about 4 ns and a spectral resolution of approximately 1 cm⁻¹. Compared to the old setup this is an improvement of more than two orders of magnitude. In addition, because of the high signal-to-noise the measurements can now be carried out in a few minutes instead of the previously required measurement periods of over twelve hours.

After the series of preliminary measurements, experimental runs were carried out on infrared multiphoton excited SF₆ and OCS. For SF₆ the population changes in the ν_1 mode were measured after infrared multiphoton excitation. As in the spontaneous Raman experiment previously funded under this contract [1-3], the CO₂ laser was tuned to the 10.6 μ m P(20) line, which is in resonance with the ν_3 mode of SF₆ at 965 cm⁻¹. We monitored the coherent anti-Stokes signal from the 0 \rightarrow 1 transition, as well as the signal from highly excited states in the

quasicontinuum, shifted by 20 cm^{-1} from the band head. As the infrared fluence is increased, the coherent anti-Stokes signal from the $0 \rightarrow 1$ transition decreases quickly because of the depletion of the ground state population, while the coherent anti-Stokes signal from the quasicontinuum increases. This is a clear indication that the vibrational energy of the ν_1 mode increases as a result of the infrared pumping of the ν_3 mode, in agreement with our previously reported spontaneous Raman experiments [1].

Since the coherent anti-Stokes signal is proportional $|\chi^{(3)}|^2$ one can quantitatively analyze the observed changes in coherent anti-Stokes signal. For the $0 \rightarrow 1$ transition one has $|\chi^{(3)}|^2 \propto (\rho_1 - \rho_0)$ [2,4] where ρ_1 and ρ_0 are the population density of the first excited and ground state, respectively. On the other hand, from the spontaneous Raman experiments, we determined the *total* energy stored in the ν_1 mode as a function of infrared fluence. If one now assumes an equilibrium energy distribution within the ν_1 ladder, one can calculate the population difference $\rho_1 - \rho_0$ from the total energy obtained from the spontaneous Raman experiments. The excellent agreement between the measured ground state coherent anti-Stokes signal and the calculated value of $(\rho_1 - \rho_0)^2$ suggests that the distribution within the ν_1 mode is close to equilibrium.

Although the population in the quasicontinuum must increase as the population in the low excitation states is depleted, the data do not show a large increase in the signal from the quasicontinuum region. This can be attributed to the fact that the coherent anti-Stokes signal from level n is proportional to $(\rho_{n+1} - \rho_n)^2$. In the quasicontinuum, for large n , the population difference between adjacent levels can be expected to be small.

The most detailed measurements were performed on infrared multiphoton excited OCS. This three atom-molecule has three vibrational degrees of freedom. The overtone of one of these, the ν_2 mode at 527 cm^{-1} , can be pumped by the CO_2

laser. Because of the cross-anharmonicity of the two modes, the population in the ν_2 mode can be monitored by observing the coherent anti-Stokes signal from the ν_1 mode at 859 cm^{-1} . With 100-ns CO_2 laser pulses it was found that the distribution within the ν_2 ladder is nearly equilibrium. In fact, even though initially only the first overtone level ($\nu = 2$) is populated, the distribution equilibrates *extremely* rapidly because of collisions. This rapid equilibration only occurs within the ν_2 ladder. No transfer of energy to other modes (e.g., the ν_1 mode) is observed. Therefore OCS provides a convenient way to study the interaction of a nearly isolated anharmonic oscillator with monochromatic infrared photons. Currently, we are carrying out systematic measurements of the population in this mode for various time-delays, pressures, and infrared laser wavelengths.

As these first measurements clearly show, coherent anti-Stokes Raman spectroscopy is a powerful tool for studying intramolecular dynamics. In addition to continue the current studies on OCS, and extending them to include other molecules, such as SO_2 , we are planning several improvements of the current setup.

1. The current CO_2 laser system will be replaced with a 10-Hz picosecond mode-locked CO_2 laser. Combined with the streak camera, the system will have picosecond time resolution. In addition, the higher repetition rate will result in a better signal-to-noise ratio.
2. Instead of a low pressure bulk sample, a molecular beam machine will be used. Because of the supersonic expansion, the sample molecules are cooled, so that the distribution of the initial states can be greatly narrowed.

With these improvements, it will be possible to further our understanding of intramolecular dynamic processes, not only for infrared multiphoton excitation, but also for a broad range of other physical and chemical phenomena.

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2. Jyhpyng Wang, Kuei-Hsien Chen and Eric Mazur, "Raman Spectroscopy of Infrared Multiphoton Excited Molecules," *Laser Chemistry* **8**, 97 (1987).
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4. M. D. Levens, *Introduction to Nonlinear Laser Spectroscopy* (Academic Press, New York, 1982).

ANNUAL REPORT OF
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b. Papers Published in Refereed Journals

K.-H. Chen, J. Wang, and E. Mazur, "Nonthermal Intramolecular Vibrational Energy Distribution in Infrared Multiphoton Excited CF_2Cl_2 ," *Phys. Rev. Lett.* **59**, 2728-2731 (1987). (Partially supported by ARO DAAG29-85-K-0060)

J. Wang, K.-H. Chen, and E. Mazur, "Raman Spectroscopy of Infrared Multiphoton Excited Molecules," *Laser Chemistry* **8**, 97-122 (1988). (Partially supported by ARO DAAG29-85-K-0060)

J. Wang, K.-H. Chen, and E. Mazur, "Energy Localization in Infrared Multiphoton Excited CF_2Cl_2 Studied by Time-Resolved Raman Spectroscopy," *IQEC 1988 Techn. Digest*, 496-497 (1988). (Partially supported by ARO DAAG29-85-K-0060)

c. Books (and sections thereof) Submitted for Publication

E. Mazur, "Can Chemical Reactions be Controlled with Picosecond Infrared Lasers?" *Proceedings of the Electrochemical Society*. (Partially supported by ARO DAAG29-85-K-0060)

d. Books (and sections thereof) Published

E. Mazur, K.-H. Chen, and J. Wang, "Highly Nonthermal Intramolecular Energy Distribution in Isolated Infrared Multiphoton Excited CF_2Cl_2 ," in *Laser Spectroscopy VII*, ed. S. Svanberg (Springer Verlag, 1988), pp. 236-238. (Partially supported by ARO DAAG29-85-K-0060)

E. Mazur, "The Interaction of Intense Picosecond Infrared Pulses with Isolated Molecules," in *Atomic and Molecular Processes with Short Intense Laser Pulses*, Ed. A. Bandrauk (Plenum, 1988), pp. 329-336. (Partially supported by ARO DAAG29-85-K-0060)

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

E. Mazur, "Can Chemical Reactions be Controlled with Picosecond Infrared Lasers?" Annual Meeting of the Electrochemical Society, Chicago, 1988.

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

J. Wang, K.-H. Chen, and E. Mazur, "Energy Localization in Infrared Multiphoton Excited CF_2Cl_2 Studied by Time Resolved Raman Spectroscopy," XVI Int. Conf. Quantum Electronics 1988, Tokyo, Japan, June 1988, pp. 496-497. (Partially supported by ARO DAAG29-85-K-0060)

J. Wang, K.-H. Chen, C.-Z. Lu, L. Avilés, and E. Mazur, "Raman Scattering Studies of Infrared Multiphoton Excited Molecules," Gordon Conference, New London, June 1988. (Partially supported by ARO DAAG29-85-K-0060).

i. Honors/Awards/Prizes

Eric Mazur — Presidential Young Investigator Award, May 1988.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.

Mr. Kuei-Hsien Chen, and Jyhpyng Wang

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

Personnel

Prof. R. W. Brockett
Asst. Prof. J. J. Clark
Prof. Y. C. Ho
Assoc. Prof. D. D. Yao
Dr. H. Chen
Dr. F. Lin
Dr. S. Strickland
Mr. G. Feigen
Mr. D. Friedman

Mr. M. Fu
Mr. P. Glasserman
Mr. W. Gong
Mr. J.J. Hu
Mr. S. Li
Mr. M. Mitchell
Mr. W. Nowlin
Mr. P. Vaikili

III.1 CMOS Current Mode Implementation of Sensor Processing Networks. J. J. Clark, R. W. Brockett, D. Friedman, and M. Mitchell, Contract N00014-84-K-0465; Research Unit 9.

Work in this research unit has continued on a program started in the previous year that is concerned with the development of "smart sensor" technology. The goals of this research are to develop integrated sensor/sensor processing circuitry which will combine arrays of sensing elements with information processing circuitry which will extract useful information from the raw sensory data. To this end, we are working on three different projects. The first involves the construction of pure sensor arrays (no information processing circuitry). We have constructed sensor arrays (containing 32×32 and 64×64 sensing elements) which sense magnetic field, and differential strain. We plan to fabricate a photosensor array. These devices will give us the base from which to develop the integrated sensor/processing "smart sensor" arrays. The second project involves the development of sensor processing circuitry that performs spatial filtering operations. These operations are of universal importance in processing spatially sampled sensory data. They can perform spatial

smoothing, or averaging, edge detection, or feature extraction to allow the detection of complex shapes. The third component of our research program involves the development of neural network circuitry for further processing of the filtered sensory data. These "neural network" systems can provide operations such as feature based classification and recognition of simple objects. The long-range goal of this program is to develop integrated sensor chips which will "understand" the data that it is sensing. The following sections outline the progress made in the last year towards this lofty goal.

Magnetic Field Sensor Array — We have continued the development of the large-scale CMOS magnetic sensor array started in the previous year. We have fabricated an improved version of the array (a 32×32 element array) which eliminates the process induced column to column offset voltages observed in the initial design. There still remains sensor to sensor relative offset voltages. These offsets, however, can be compensated for off-chip with a calibration-compensation circuit. This calibration-compensation circuit, which we have constructed, performs a calibration phase wherein the sensor to sensor offset voltages are measured in a zero field situation and these values are stored in RAM (or permanently stored in an EPROM). Then, when the sensor is scanned these offsets are compensated for by adjusting the output based on the stored offsets. We are now able to perform field mapping experiments on the arrays and can begin to apply the chips to the robotics applications for which they were designed.

We have tested the chip for its sensitivity to nonmagnetic disturbances and we have found that it is somewhat sensitive to temperature, but is insensitive to light. The chip is sensitive to spatial gradients in the stress experienced by the silicon substrate. This is due to the piezoresistive properties of silicon which means that the conductance of a transistor is a function of the applied stress. However, since the magnetic field sensors essentially measure the difference in conductance

between two spatially separate transistors, the output of the sensor is a function of the difference in applied stress between these two transistors. Since these transistors are very close spatially one obtains a spatial derivative of the applied stress. One can use the chip, then, as a strain gauge array or pressure transducer, an application we will investigate in the coming year. For use as a magnetic field sensor one must be very careful when packaging the device in order to minimize any residual stresses which will cause offsets. Also one must minimize the propagation of stresses from forces applied to the package to the chip itself. We will be investigating these effects more closely in our development of our magnetic field based tactile sensor [1].

Integrated Sensor and Spatial Filter Arrays — We have proposed a novel method for obtaining spatial filtering or convolutional operations using current mode techniques. These techniques involve the use of current mirrors to scale or weight sensor signals by coefficients specifiable during design of the circuits. Coupling these weighting circuits with a current summation and amplification circuit results in a circuit that computes weighted sums of spatially disparate sensor outputs. We have simulated the operation of these convolution cells and these have demonstrated that the circuits do work as intended. We are currently laying out, and will fabricate shortly, a test circuit which contains a number of the convolution cells combined with magnetic field sensors. This test chip will allow us to examine the characteristics of the convolution elements. We are also in the process of designing a magnetic field sensor chip which includes two stages of convolution circuitry which will perform a smoothing operation followed by a Laplacian differential operation. This output of this chip will be an "edge" enhanced version of the applied magnetic field pattern.

Current Mode Realizations of Electronic Neural Networks — We have developed a design for an electronic neural network that uses the same circuit that performs the spatial convolution described in the previous section. This circuit

implements the "synapse" of an electronic neuron with a current mirror. The weight, or strength of the synapse is adjusted by altering the size of the transistors in the current mirror. Our electronic neuron is a general purpose one and with it one can construct many types of neural networks, such as the Hopfield network or a back-propagation network (for a review of different types of neural networks, see [2]). We have simulated our neuron using the SPICE simulation package and have shown it to behave in the appropriate fashion (*i.e.*, the neurons output is a sigmoidal function of the sum of its inputs). We are currently designing and laying out an integrated circuit in 2 micron CMOS technology which will contain a number (probably a Hebbian type of feedforward learning rule. This chip will be used to examine symmetry breaking in feedforward networks (work being done with Prof. Alan Yuille of Harvard and Dr. Dan Kammen of Caltech), and will also provide information on the dynamics of feedforward networks (work being done in conjunction with Prof. Robert Westervelt's research group).

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1. J. J. Clark, "A Magnetic Field Based Compliance Matching Sensor for High Resolution, High Compliance Tactile Sensing," IEEE Robotics and Automation Conference, Philadelphia, PA, May 1988
2. R. P. Lippman, "An Introduction to Computing with Neural Nets," IEEE ASSP Magazine, April 1987

III.2 Decision and Control — Discrete Event Dynamic Systems Study. Y. C. Ho and D. D. Yao, Contracts N00014-84-K-0465, ONR-N00014-86-K-0075, NSF-ESC-85-15449, NSF-CDR-85-001-08, and NSF-ECS-86-58157; Research Unit 10.

The field of Discrete Event Dynamic Systems (DEDS) received further evidences of growing interest and support during 1988: (i) A special workshop devoted to DEDS sponsored by NSF took place in June 19-22, 1988. (ii) A special issue of the Proceedings of IEEE devoted to DEDS will be published in February, 1989. In our research effort, the analysis tool of Perturbation Analysis (PA) for DEDS also finally came into its own both in terms of theoretical foundation and general acceptance during the past year. The main theoretical issue in the development of PA revolves around the question of the interchange of expectation and differentiation operators. A number of theoretical and computational developments partially reported last year are now accepted by the scientific community at large. In particular, the smoothed PA and the extended PA techniques [1, 2] demonstrated the generality of the sample path approach of PA. More generally, PA can now be viewed in the more general framework of the efficient generation of sample paths in real or simulated time for discrete event systems. This has led to new insights to the design of simulation languages [3].

David Yao's work in the past year has been focused on the following two topic areas:

The notion of strong stochastic convexity (SSCX) has been developed in [4] to characterize a family of random variables parameterized by a vector parameter. This property is often indispensable in the parametric optimization of discrete stochastic systems. It is shown that SSCX is preserved under random mixture, random summation, any increasing and convex operations, and is hence enjoyed by a wide range of families of random variables. It is noted that the dynamics of

**ANNUAL REPORT OF
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a. Papers Submitted to Refereed Journals (and not yet published)

J. J. Clark, "Singularity Theory and Phantom Edges in Scale Space," IEEE Transactions on Pattern Analysis and Machine Intelligence, to be published in Sept. 1988 issue.

J. J. Clark, "Authenticating Edges Produced by Zero Crossing Algorithms," IEEE Transactions on Pattern Analysis and Machine Intelligence.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

J. J. Clark and D. Friedman, "Novel Circuit Techniques for Sensor Arrays," Second Workshop on Synthetic Microstructures in Biological Research, Airlie, VA, March 1988 (no published Proceedings).

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

J. J. Clark, "A Magnetic Field Based Compliance Matching Sensor for High Resolution, High Compliance Tactile Sensing," IEEE Robotics and Automation Conference, Philadelphia, PA, May 1988 (published in the Conference Proceedings), pp. 772-777.

J.J. Clark, "CMOS Magnetic Sensor Arrays," IEEE Solid-State Sensors and Actuators Workshop, Hilton Head Island, SC, June 1988 (published in the Workshop Technical Digest).

i. Honors/Awards/Prizes

J. J. Clark, IEEE Acoustic Speech and Signal Processing Society Paper Award for best transactions paper on Signal Processing by authors under thirty years of age, April 15, 1988.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.

Mr. D. Friedman and Mr. W. Nowlin

many stochastic systems can be expressed in recursive equations that only involve simple and well-behaved operators. A simple example is the Lindley equation that relates the waiting time of the n -th job in a GI/G/1 queue to the interarrival and service times recursively through two operators: $+$ and \max , both are increasing and convex. Therefore, the closure property of SSCX indicates that the convexity of the waiting time is implied by the convexity (concavity) of the service (interarrival) times (which are given data). Another example is the convexity of the reciprocal of the throughput of a closed Jackson network with respect to server utilization at the stations. The direct algebraic proof of this classical result is notoriously tedious. Based on the closure property of SSCX, this result turns out to be a very special case of a much more general model, where much stronger results can be established in the most straightforward manner. The notion of SSCX has already found useful applications in the stochastic optimization of discrete event systems using perturbation analysis.

In practice many discrete stochastic systems are controlled by simple operating rules, such as the threshold rule (*e.g.*, turn off the input when the congestion reaches the upper threshold, and turn off the output when the congestion reaches the lower threshold), and the priority rule (*e.g.*, jobs are grouped into different priority classes and processed as such in a computer-communication network). An interesting problem is to identify the most general environment in which such rules are proved to be optimal. In [5], the optimality of the threshold rule is established for a general queueing system where the input and output processes are modeled as count processes with stochastic intensities, subject to state-dependent capacity limits. In [6, 7], the optimality of the priority rule is shown to be a direct consequence of the "conservation laws," which are prevalent in a wide class of systems. The conservation laws lead to a very rich structure of the control problem, so that it can be transformed into an optimization problem with a *polymatroid* feasible re-

gion. The optimality of priority rules then follows from basic results in polymatroid theory.

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2. W. Gong and Y. C. Ho, "Smoothed Perturbation Analysis of Discrete Event Dynamic Systems," *IEEE Transactions on Automatic Control*, 1987.
3. Y.C. Ho, S. Li, and P. Vakili, "On the Efficient Generation of Discrete Event Sample Path Under Different Systems Parameter Values," *International Journal of Mathematics and Computers in Simulation*, to appear, 1989.
4. J. G. Shanthikumar and D. D. Yao, "Strong Stochastic Convexity: Closure Properties and Applications," Manuscript, Harvard University, February, 1988.
5. H. Chen and D. D. Yao, "Optimal Intensity Control of a Queueing System," Manuscript, Harvard University, May, 1988.
6. J. G. Shanthikumar and D. D. Yao, "Multiclass Queueing Systems; Polymatroid Structure and Optimal Scheduling Control," Manuscript, Harvard University, April, 1988.
7. K. W. Ross and D. D. Yao, "Optimal Dynamic Scheduling in Jackson Networks," *IEEE Transactions on Automatic Control* (to appear).

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

P. Glasserman, "Infinitesimal Perturbation Analysis of a Birth and Death Process," to appear in *OR Letters*.

P. Glasserman and Y.-C. Ho, "Aggregation and Perturbation Analysis of Queueing Networks," submitted to *Performance Evaluation*.

K.W. Ross and D.D. Yao, "Optimal Dynamic Scheduling in Jackson Networks," to appear in *IEEE Transactions on Automatic Control*.

H. Chen and D.D. Yao, "Optimal Intensity Control of a Queueing System," submitted to *IEEE Transactions on Automatic Control*.

J.G. Shanthikumar and D.D. Yao, "Second-Order Stochastic Properties in Queueing Systems," submitted to *IEEE Proceedings*.

J.G. Shanthikumar and D.D. Yao, "Spatiotemporal Convexity of Stochastic Processes and Applications," submitted to *Mathematics of Operations Research*.

J.G. Shanthikumar and D.D. Yao, "Monotonicity Properties in Cyclic Queueing Networks with Finite Buffers," submitted to *Queueing Networks with Blocking*.

J.G. Shanthikumar and D.D. Yao, "Strong Stochastic Convexity: Closure Properties and Applications," submitted to *Advances in Applied Probability*.

J.G. Shanthikumar and D.D. Yao, "Multiclass Queueing Systems: Polymatroid Structure and Optimal Scheduling Control," submitted to *Operations Research*.

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X.R. Cao and Y.C. Ho, "Estimating the Sojourn Time Sensitivity in Queueing Networks Using Perturbation Analysis," *J. of Optimization Theory and Applications* **53**(3), 353-375 (1987).

J.G. Shanthikumar and D.D. Yao, "Stochastic Monotonicity of the Queue Lengths in Closed Queueing Networks," *Operations Research* **35** (4), 583-588 (1987).

X.-R. Cao and Y.-C. Ho, "Sensitivity Analysis and Optimization of Throughput in a Production Line with Blocking," *IEEE Transactions on Automatic Control* **AC-32** (11), 959-967 (1987).

D.D. Yao, "The Arrangement of Servers in an Ordered-Entry System," *Operations Research* **35** (5), 759-763 (1987).

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D.D. Yao and S.C. Kim, "Reducing the Congestion in a Class of Job Shops," *Management Science* **33** (9), 1165-1172 (1987).

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W.-B. Gong and Y.-C. Ho, "Smoothed (Conditional) Perturbation Analysis of Discrete Event Dynamical Systems," *IEEE Transactions on Automatic Control* **AC-32** (10), 858-866 (1987).

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J.G. Shanthikumar and D.D. Yao, "Second-Order Properties of the Throughput of a Closed Queueing Network," *Mathematics of Operations Research* **13** (3), 524-534 (1988).

g. **Invited Presentations at Topical or Scientific/Technical Society Conferences**

Y. C. Ho, NSF Emerging Technology Conference, Washington, D.C., October 29, 1987.

Y. C. Ho, IEEE Conference on Decision and Control, Los Angeles, CA, December 9, 1987.

Y.C. Ho, Winter Simulation Conference, Atlanta, GA, December 14, 1987.

Y.C. Ho, National Taiwan University, Taiwan, ROC, January 5, 1988.

Y.C. Ho, National Jiaotong University, Taiwan, ROC, January 7, 1988.

Y.C. Ho, Bell Telephone Laboratories, January 21, 1988.

Y.C. Ho, Rensselaer Polytechnic Institute, February 4, 1988.

Y.C. Ho, University of California, Davis, March 28, 1988.

Y.C. Ho, Stanford University, March 29, 1988.

Y.C. Ho, 30 Years of Optimal Control Conference, URI, June 1, 1988.

Y.C. Ho, American Control Conference, Atlanta, GA, June 14, 1988.

Y.C. Ho, NSF Conference on Discrete Event Dynamic Systems, June 19-22, 1988.

Y.C. Ho, Conference on Intelligent Control

D.D. Yao, ORSA/TIMS National Meeting, St. Louis, October, 1987.

D.D. Yao, Digital Equipment Corporation, Applied Artificial Intelligence Lab., November, 1987.

D.D. Yao, IEEE Conference on Decision and Control, Los Angeles, December, 1987.

D.D. Yao, Xerox Corporation, Mechanical Science Lab., March, 1988.

D.D. Yao, GTE Laboratories, March, 1988.

D.D. Yao, ORSA/TIMS National Meeting, Washington, D.C., April, 1988.

D.D. Yao, International Workshop on Queueing Networks with Blocking, Raleigh, NC, May, 1988.

D.D. Yao, Applied Probability in Large Scale Stochastic Systems, Chapel Hill, NC, May, 1988.

D.D. Yao, University of Maryland, Systems Research Center, May, 1988.

D.D. Yao, University of Waterloo, May, 1988.

D.D. Yao, University of Toronto, June, 1988.

D.D. Yao, NSF Workshop on Discrete Event Dynamic Systems, Virginia, June, 1988.

D.D. Yao, Rensselaer Polytechnic Institute, August, 1988.

i. Honors/Awards/Prizes

Y. C. Ho was elected to the National Academy of Engineering.

Y. C. Ho served as General Chairman of the 1987 IEEE Robotics and Automation Conference.

Y. C. Ho was elected to the post of President IEEE Robotic and Automation Council for 1988.

Best paper award (for paper in the IEEE Trans. on Automatic Control during 1985-86) to X. Cao for work done while holding a postdoc at Harvard.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1988.

Drs. F. Lin, H. Chen, S. Strickland and Messrs. P. Glasserman, W. Gong, G. Feigen, P. Vakili, S. Li, M. Fu, and J.J. Hu

IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. T. T. Wu
Prof. R. W. P. King
Dr. J. M. Myers
Dr. H.-M. Shen
Mr. M. F. Brown

Mr. G. Fikioris
Mr. N. Filippopoulos (until April 30, 1988)
Mr. D. K. Freeman
Ms. M. Owens
Ms. B. H. Sandler

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in the area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include dipoles, insulated antennas, traveling-wave antennas and arrays, crossed dipoles, and loops near the boundary between two media such as air and the earth or sea, or the oceanic crust and sea water; the properties of lateral electromagnetic waves; lateral waves and reflected waves in horizontally-layered media; the generation, propagation, and reception of lateral electromagnetic pulses; arrays

of antennas along curved lines; and solitary electromagnetic pulses with slow rates of decay.

IV.1 Analytical and Numerical Determination of the Fields of Antennas near an Interface Between Two Half-Spaces with Significantly Different Wave Numbers. T. T. Wu, R. W. P. King, B. H. Sandler, and M. Owens, Contract N00014-84-K-0465; Research Unit 11.

Electromagnetic surface waves of a type known as *lateral waves* are excited along a boundary between two electrically different half-spaces by both vertical and horizontal electric dipoles located near or on that boundary. Beginning with the papers by Wu and King [1], [2], and King and Wu [3] for the horizontal dipole and by King [4] for the vertical dipole, the general integrals for the components of the electric and magnetic fields were integrated to obtain simple, accurate and continuous formulas valid over radial distances from very close to the source to infinity. These apply specifically to the field in Region 1 and along the boundary in Region 2, subject to the inequality $|k_1| \geq 3|k_2|$ where k_1 and k_2 are the wave numbers of the two half-spaces.

This early work was then extended to include the determination of integrated formulas for the field throughout Region 2 (the half-space in which the lateral wave travels) for both horizontal [5] and vertical [6] electric dipoles located near the boundary in Region 1. The field in Region 2 is shown to include an outward-traveling spherical wave and a lateral wave. The availability of integrated formulas for the field in Region 2 has permitted a detailed study of the properties of the lateral-wave part of the field, including the locus of the Poynting vector, the maximum depth of penetration of the lateral wave into Region 2, and the fraction of power associated with the lateral wave.

During the current reporting period, these results have been further extended to obtain simple integrated formulas for the complete electromagnetic field (not just

the far field) at any point in the air (Region 2) when the dipole is at a height d also in the air [7], [8]. Of particular interest in radio communication over the surface of the earth is the field at any point in Region 2 (air) when the dipole is on the surface of Region 1 (earth or sea). This field is completely and accurately given by the general formulas with $d = 0$. Using the large-argument approximation of the Fresnel-integral terms, simple expressions are also obtained for the complete far field of the unit vertical dipole on the surface of Region 2. Graphs of the magnitude of $E_{2\theta}(r_0, \theta)$ for a unit vertical dipole for four different Regions 1 (salt water, lake water, wet earth, dry earth) show that the oscillations in the field patterns due to the interference between the direct field and the field reflected from the imperfectly conducting Region 1 decrease in amplitude with increasing conductivity σ_1 . They disappear when Region 1 is a perfect conductor with $\sigma_1 = \infty$.

References:

1. T. T. Wu and R. W. P. King, "Lateral Waves: A New Formula and Interference Patterns," *Radio Science* **17**, 521-531 (1982).
2. T. T. Wu and R. W. P. King, "Lateral Waves: New Formulas for $E_{1\phi}$ and E_{1z} ," *Radio Science* **17**, 532-538 (1982); Correction, **19**, 1422 (1984).
3. R. W. P. King and T. T. Wu, "Lateral Waves: Formulas for the Magnetic Field," *J. Appl. Phys.* **54**, 507-514 (1983); Erratum, **56**, 3365 (1984).
4. R. W. P. King, "New Formulas for the Electromagnetic Field of a Vertical Electric Dipole in a Dielectric or Conducting Half-Space near its Horizontal Interface," *J. Appl. Phys.* **53**, 8476-8482 (1982); Erratum, **56**, 3366 (1984).
5. R. W. P. King, M. Owens, and T. T. Wu, "Properties of Lateral Electromagnetic Fields and Their Application," *Radio Science* **21**, 13-23 (1986).
6. R. W. P. King, "Properties of the Lateral Electromagnetic Field of a Vertical Dipole and Their Application," *IEEE Trans. Geosci. & Remote Sensing* **GE-24**, 813-825 (1986).
7. R. W. P. King, "Electromagnetic Surface Waves," invited feature article in *IEEE Antennas and Propagat. Society Newsletter*, **28**, 5-11 (1986).
8. R. W. P. King, "Lateral Electromagnetic Surface Waves and Pulses," invited paper, presented at the Heinrich Hertz Symposium, Universität Karlsruhe, FRG, March 14 and 15, 1988.

IV.2 Theoretical Study of Lateral-Wave Propagation in Horizontally-Layered Media. R. W. P. King, B. H. Sandler, and T. T. Wu, Contract N00014-84-K-0465; Research Unit 11.

The theoretical work described in the preceding topic is concerned with the electromagnetic field generated by dipoles near the boundary between two homogeneous but electrically different half-spaces. Both half-spaces are assumed to be isotropic, except in the recent study by Pan [1] in which one of the half-spaces is anisotropic in the conductivity with the horizontal values $\sigma_x = \sigma_y$ different from the vertical value σ_z . This is a special form of horizontal layering. In a more general form, one of the half-spaces is composed of a succession of n horizontally bounded layers each with arbitrary thickness and arbitrary wave number. Each layer is homogeneous and isotropic but the wave number is discontinuous across the boundaries. Below the n^{th} layer the rest of the half-space is homogeneous and isotropic to infinity. This layered model is used by geophysicists in the study of the oceanic crust. The general integrals for the electromagnetic field of a dipole in the one homogeneous, isotropic half-space separated from the second such half-space by the n horizontal layers of arbitrary electrical properties have been formulated, and from them simple integrated formulas have been obtained.

These general formulas have then been applied to a layered region with the properties of microstrip [2]. Microstrip can be considered a three-layered region consisting of air-dielectric-conductor. Its properties can be investigated in terms of the electromagnetic field generated by a horizontal electric dipole on the air-dielectric surface—which can be looked upon as an element of a transmission line or antenna—and vertical electric dipoles in the dielectric—which correspond to elements of a vertical conductor joining a horizontal circuit through the substrate to the conducting plane. The determination of the electromagnetic field in relatively simple form is possible when the following inequalities are satisfied: $k_0^2 < |k_1^2| < |k_2^2|$, where k_j , $j = 0, 1, 2$, are the wave numbers of Region 0 (air), Region 1 (dielectric),

and Region 2 (conductor), respectively. Formulas are derived for the tangential electric field along the air-substrate boundary in microstrip and the vertical electric field in its interior when excited by a unit horizontal electric dipole at $\rho = 0$ on the boundary $d = 0$. Although the integrated formulas are simpler and more readily understood than the integrals they approximate, the fields they represent are complicated. Along the boundary, $E_\rho(\rho, \phi, 0)$ and $E_\phi(\rho, \phi, 0)$ each consists of two waves, a lateral wave characterized by the exponential factor $\exp(ik_0\rho)$ that travels in the air with the velocity c and a direct wave characterized by the exponential factor $\exp(ik_1\rho)$ that travels in the dielectric substrate with the velocity $c\epsilon^{-1/2}$. These two components determine the interaction between currents in conductors located on the air-substrate boundary. $E_{1z}(\rho, \phi, z)$ in the substrate also includes a lateral wave that travels along the surface and then down into the substrate and a direct wave that travels directly through the substrate. It determines the coupling between horizontal currents in conductors on the air-substrate boundary and vertical currents in connections from the air surface to the conducting plane. It is noteworthy that, when a dipole operating at a single fixed frequency generates two waves that travel outward with different phase velocities, the effect is similar to—but is not—dispersion. In the case at hand, the permittivities of air and the substrate are assumed to be constants independent of the frequency so that the phase velocities associated with them are also frequency-independent. However, a signal that propagates without dispersion at two different phase velocities is distorted in transmission in a manner similar to that observed with dispersion. If the permittivity of the substrate is frequency-dependent, the part of the signal traveling in it will suffer dispersion, the lateral-wave part in the air will not.

The general formulas derived for n -layered regions have also been applied to a three-layered region consisting of sea water-sediment-oceanic crust. A systematic study has been made [3] of the transverse components E_ρ and E_ϕ on the sea floor

in their dependence on the conductivity and thickness of the sediment and the conductivity of the underlying crustal rock. It is found that E_ρ and E_ϕ are both very sensitive to all three parameters and that there is no combination that provides a simultaneously satisfactory fit for both E_ρ and E_ϕ . This is at variance with the calculations of Young and Cox [4] which show a negligible effect on E_ϕ of the properties of 8 layers to a depth of 30 km but a very strong effect on E_ρ . The result suggests again the importance of anisotropy in the uppermost crustal conductivity [1]. The theory for n horizontal layers is also being applied to the case of an eight-layered model used in the study of the conductivity of the oceanic crust and to a three-layered region consisting of air-arctic ice-sea water.

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1. W.-Y. Pan, "Surface-Wave Propagation Along the Boundary Between Sea Water and One-Dimensionally Anisotropic Rock," *J. Appl. Phys.* 58, 3963-3974 (1985).
2. R. W. P. King, "The Propagation of Signals Along a Three-Layered Region: Microstrip," *IEEE Trans. Microw. Theory & Tech.* MTT-36, 1080-1086 (1988).
3. R. W. P. King, "The Three-Layer Problem for Sediment on the Oceanic Crust," in preparation.
4. P. D. Young and C. S. Cox, "Electromagnetic Active Source Sounding Near the East Pacific Rise," *Geophys. Res. Lett.* 8, 1043-1046 (1981).

IV.3 Lateral Electromagnetic Waves from a Horizontal Antenna for Remote Sensing in the Ocean. R. W. P. King, Contract N00014-84-K-0465; Research Unit 11.

The method developed earlier under this Contract [1], [2] for finding a buried metal cylinder in the earth can be adapted to the search for cylindrical metal objects like mines and submarines in the ocean or lying on the sea floor. Because salt water has quite different properties from earth, both the theoretical adaptation and the practical application of the method involve significant modifications that are

scientifically interesting. These include the following: (a) The fluid nature of water makes it possible to locate and move both the transmitting and receiving antennas, not in the air, but in the same medium as the cylinder to be located. This greatly increases the magnitude of the receivable scattered signal and significantly reduces the possible interference by reflections from the ionosphere, because the transmission coefficient of a plane wave normally incident on the surface of the sea from the air is very small at the frequencies involved. (b) The much higher conductivity of the sea water compared to earth leads to a much greater complex wave number for electromagnetic waves. The associated wavelength is much shorter than that in the earth at the same frequency. It follows that a much lower frequency must be used in order to have the scattering cylinder with length $2h$ near resonance. Associated with the use of a lower frequency is a helpful decrease in the exponential attenuation of a traveling wave and a disadvantageous shift in the properties of lateral waves from those of the intermediate field with a radial decrease with distance of ρ^{-1} to the near field with a radial decrease of ρ^{-3} . Account is readily taken in the analysis of these important facts. A systematic study has been made [3] of the several important factors involved in the development of a method for locating submerged submarines from measurements of the scattered electromagnetic field at the surface. These involve the properties of crossed antennas in the sea at very low frequencies and the circularly polarized lateral-wave fields they generate, as well as the field scattered by a submarine and a crossed receiving antenna to detect this. Representative calculations are made to illustrate the relative orders of magnitude of the dimensions and fields involved and the required sensitivity of a receiver.

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1. R. W. P. King, "Scattering of Lateral Waves by Buried or Submerged Objects. I. The Incident Lateral-Wave Field," *J. Appl. Phys.* **57**, 1453-1459 (1985).
2. R. W. P. King, "Scattering of Lateral Waves by Buried or Submerged Objects.

II. The Electric Field on the Surface Above a Buried Insulated Wire," *J. Appl. Phys.* **57**, 1460-1472 (1985).

3. R. W. P. King, "Lateral Electromagnetic Waves from a Horizontal Antenna for Remote Sensing in the Ocean," *IEEE Trans. Antennas Propagat.*, submitted for publication.

IV.4 Lateral-Wave Propagation and Modeling of the Lithosphere. M. F. Brown, R. W. P. King, and T. T. Wu, Contracts N00014-79-C-0419 and N00014-84-K-0465; Research Unit 11.

This nine-year research program has now been concluded and a summary report of its many accomplishments has been prepared [1]. The aim of this project has been to acquire fundamental understanding in an accurate quantitative sense of the generation, propagation, and reception of electromagnetic signals—both continuous waves and pulses—in and near the sea floor. Definitive advances have been made on (1) the design of sources (horizontal and vertical antennas) for use on and near the sea floor over a wide range of frequencies; (2) the derivation of simple and accurate new formulas for the complete continuous-wave electromagnetic fields both in the sea and in the oceanic crust when this is isotropic or one-dimensionally anisotropic, and when there is a layer of sediment with arbitrary thickness; (3) the determination of the effect of irregularities in the form of vertical discontinuities along the boundary surface; (4) the direct application of the new formulas to measurements in a model tank and to data measured on the sea floor as reported by geophysicists; and (5) the derivation of new formulas for the propagation of single electromagnetic pulses along boundary surfaces.

The investigation of the properties of electromagnetic waves propagating in the presence of the sea floor has been three-pronged: (1) The exact integrals for the components of the electromagnetic field have been evaluated by numerical methods with the computer in their general form. The low-frequency forms used by geophysicists in which $\omega\epsilon$ is assumed to be small compared with σ are contained as a special

case. This allows the correct inclusion of the air-sea boundary whenever this is also involved. (2) The general integrals have been integrated analytically subject to simple conditions that are fully satisfied in virtually all practical applications. The quite simple integrated expressions have been compared with the numerical calculations and with experiment. They have then been applied to reveal the basic properties of the surface waves, their depth of penetration, and their independence of frequency and skin depth. (3) A systematic series of measurements has been carried out in a model tank to obtain direct information on the generation, propagation, scattering and detection of surface waves. Since both the theory and the measurements deal with the general formulas—not restricted by the usual geophysical limitation to very low frequencies—a complete, generally significant, and quantitatively accurate picture has been obtained of the properties of electromagnetic waves in the presence of a boundary.

Recent work has been concerned with the experimental and theoretical study of the generation and propagation of lateral electromagnetic pulses along boundaries between electrically different media. A terminated insulated antenna has been designed and tested for launching a lateral electromagnetic-field pulse. The propagation of such a pulse along an air-water boundary has been studied in detail in the model tank with various concentrations of salt in the water to adjust its conductivity over a wide range. With low conductivities, reflected pulses from the floor of the tank are observed and readily separated from the lateral-wave pulse that travels in the air. A theoretical and experimental study of the field generated by a pulsed vertical monopole over salt water is in [2]. The theory yields a precise quantitative correction to the effect of a metal ground plane underlying a pulsed short vertical monopole. This correction for replacement of the ground plane by a region of salt water involves Fresnel-integral terms which may be represented using a confluent hypergeometric function. The influence of imperfectly conducting salt

water with its associated complex wave numbers k_1 for the range of frequencies in a broadband Gaussian pulse provides a resolvable correction to the monopole field over metal even at distances $\rho \leq 1.0$ m from the source. This correction becomes more significant with increasing radial distance. Except for a narrow region in the very close vicinity of the vertical source monopole, the theoretical prediction of monopole fields to $\rho = 1.6$ m is followed closely by the experimental observations of the fields.

References:

1. T. T. Wu, R. W. P. King, and M. F. Brown, "Model Investigations of Lithospheric Propagation," Final Report, ONR Contract N00014-79-C-0419, Gordon McKay Laboratory, Harvard University, Cambridge, MA (1988).
2. M. F. Brown, "Wave Packets of Lateral Waves Due to a Vertical Monopole: Experiment and Theory," *Radio Science* **22**, 833-846 (1987).

IV.5 Lateral Electromagnetic Pulses Generated by Horizontal and Vertical Dipoles on the Boundary Between Two Dielectrics. T. T. Wu and R. W. P. King, Contract N00014-84-K-0465; Research Unit 11.

The properties and possible applications of lateral pulses generated by horizontal and vertical electric dipoles on or near the plane boundary between two electrically different media are of considerable interest. Significant progress has been made in the study of lateral-wave pulses excited by current pulses that are delta functions in time. An exact solution in terms of elementary functions has been obtained [1] in the time domain for the vertical electric field $E_z(\rho, t)$ and the transverse magnetic field $B_\phi(\rho, t)$ of a dipole located on the plane boundary $z = 0$ between air (Region 2, $z < 0$) and a perfect dielectric (Region 1, $z > 0$) when the dipole is excited by a single delta-function current pulse. The vertical electric field on the boundary consists of a two delta-function pulses that travel with the velocities c and $c\epsilon^{-1/2}$ and arrive at the times $t - \rho/c$ and $t - \rho\epsilon^{1/2}/c$. The first

pulse travels in the air, the second in the dielectric. Both pulses have the amplitude factor ρ^{-2} . Thus, the transient field at *all radial distances* has the same radial dependence as the far field along the boundary in the steady state. The field varies in a complicated manner in the interval between the two pulses with a radial dependence of $\rho^{-1/2}$. After the second pulse has passed, the electric field drops to a final static value due to the oppositely charged ends of the dipole. The horizontal magnetic field is similar, except that it drops abruptly to zero after the second pulse has passed. For comparison, the vertical electric field in the equatorial plane of the same dipole in a homogeneous dielectric has also been derived. The comparison indicates that the field along the boundary is a surface-wave or lateral pulse. Instead of a $1/\rho$ amplitude factor which is characteristic of propagation in an unbounded region, the amplitude factor of the pulsed field along the boundary is $1/\rho^2$ which is characteristic of the surface wave.

The exact evaluation of the transient field by the Fourier transformation of the general integrals has been achieved only for the components B_ϕ and E_z generated by a delta-function current in a vertical dipole on the boundary between two dielectrics [1]. These components have subsequently been reevaluated [2], [3] from the approximate, relatively simple forms previously available for the frequency domain, subject to the inequalities $|k_1|^2 \geq 9|k_2|^2$, $|k_1\rho| \geq 3|k_2\rho| \geq 3$. For dielectrics with $k_1 = k_2\epsilon^{1/2}$, $k_2 = \omega/c$, $\epsilon_{2r} = 1$, and $\epsilon_{1r} = \epsilon$, these inequalities include $\epsilon \geq 9$. The significance of this condition in the time domain is of interest. Note that $\epsilon \geq 9$ means that, in the derivation of the steady-state formulas, terms that are of the order ϵ^{-1} have been neglected by omission where convenient. Because of this approximation the second pulse $\delta(t - \rho\epsilon^{1/2}/c)$ is absent in the approximate formulas. The ratio of its amplitude coefficient to that of the first pulse $\delta(t - \rho/c)$ is ϵ^{-2} or $\epsilon^{-3/2}$, both of which are very small when $\epsilon \geq 9$. A numerical calculation of the exact and approximate formulas for $B_{2\phi}$ and E_{2z} in the range $\rho/c < t < \rho\epsilon^{1/2}/c$ between

the two pulses has been tabulated for two values of ϵ . The comparison shows quite remarkable agreement between the two superficially quite different formulas.

Since the approximate formulas are excellent approximations for B_ϕ and E_z , they have also been used to evaluate E_ρ for the vertical dipole and all six of the more complicated components of the horizontal electric dipole. This approximate approach has also been used to evaluate the transient field when the dipole is excited by a Gaussian pulse [2], [3]. As with the delta-function pulse, the omission of small terms with magnitudes smaller than ϵ^{-1} in the frequency-domain formulas must lead to the nonappearance of a second pulse whose amplitude is very much smaller than the first pulse because it is multiplied by a factor of the order ϵ^{-2} . The approximate formulas can be expected to be quite accurate before the second pulse arrives and to give the correct final static values. The vertical electric field has been plotted as a function of time for seven different radial distances. The shape of the pulse is determined by the relative contributions from the four terms appearing in the final formula for $E_{2z}(\rho, t)$ with their very different dependences on the radial distance and the time. The third term represents the rapid increase in the vertical electric field as the pulse passes and leaves the final electrostatic field of the charged infinitesimal dipole. This part of the field decreases as $1/\rho^3$ with distance. The second term is a Gaussian pulse that travels with the phase velocity c and with a decrease in amplitude of $1/\rho^2$. The first term is the time derivative of the Gaussian pulse; it decreases with distance only as $1/\rho$ so that it persists for much greater distances than does the $1/\rho^2$ term. Unlike the field with the delta-function pulse or the steady-state field, the fourth term due to the Fresnel integral does not completely cancel the $1/\rho$ term. Its behavior is similar to a negative derivative of the Gaussian pulse. Since the $1/\rho$ term is not completely cancelled by the Fresnel-integral term, it may be presumed that the Gaussian pulse decreases more slowly in amplitude with increasing radial distances than the steady-state field. The degree

of cancellation of the $1/\rho$ term must increase as the pulse width is made smaller, decrease as it is made larger. That is, the greater the low-frequency content of the Gaussian pulse, the slower is its decrease in amplitude at large radial distances.

References:

1. T. T. Wu and R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on the Boundary Between Two Dielectrics," *J. Appl. Phys.* **62**, 4345-4355 (1987).
2. R. W. P. King, "Lateral Electromagnetic Surface Waves and Pulses," invited paper, presented at the Heinrich Hertz Symposium, Universität Karlsruhe, FRG, March 14 and 15, 1988.
3. R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on a Plane Boundary Between Dielectrics," *Journal of Electromagnetic Waves and Applications* **2**, 225-243 (1988).

IV.6 Lateral Electromagnetic Waves (Manuscript for Book). R. W. P. King, T. T. Wu, M. Owens, and B. H. Sandler, Contracts N00014-84-K-0465 and N00014-79-C-0419; Research Unit 11.

It has become a tradition in the publication of researches in the area of electromagnetic phenomena to periodically summarize and coordinate major segments in book form. Accordingly, a manuscript is in preparation which contains the results of current and past researches on lateral electromagnetic waves that have been supported by the above JSEP and ONR Contracts. The chapter headings are: 1. Historical and Technical Review of Electromagnetic Surface Waves; Introduction to Lateral Waves, 2. Electromagnetic Preliminaries, 3. The Electromagnetic Field of a Vertical Dipole in the Presence of a Plane Boundary, 4. Applications of the Theory of the Vertical Dipole near The Boundary Between Two Half-Spaces, 5. The Electromagnetic Field of a Horizontal Electric Dipole in the Presence of a Plane Boundary, 6. Interference Patterns; Comparison of Approximate Formulas with General Integrals and Measurements, 7. Applications of the Theory of the Horizontal Dipole near the Boundary Between Air and Earth or Sea, 8. The

Measurement of the Conductivity of the Oceanic Lithosphere with a Horizontal Antenna as the Source, 9. Lateral Waves in a One-Dimensionally Anisotropic Half-Space, 10. The Propagation of Lateral Electromagnetic Waves in Air over Vertical Discontinuities, 11. The Horizontally Layered Half-Space, 12. The Three-Layer Problem for Sediment on the Oceanic Crust, 13. The Propagation of Signals Along a Three-Layered Region: Microstrip, 14. Lateral Electromagnetic Pulses Generated by Vertical Dipoles, 15. Approximate Formulas for Lateral Electromagnetic Pulses Generated by Vertical and Horizontal Electric Dipoles, 16. Antennas in Material Media Near Boundaries: The Bare Metal Dipole, 17. Antennas in Material Media Near Boundaries: The Terminated Insulated Antenna, 18. The Wave Antenna.

IV.7 Theoretical Study of Isolated and Coupled Strip Antennas. R. W. P. King, Contract N00014-84-K-00465; Research Unit 11.

The properties of the isolated strip antenna of width $2w$ are usually obtained from those of the circular tubular antenna of radius a by an application of the well-known equivalence, $w = 2a$. The parameters of the strip transmission line with conductors of width $2w$ and separated by the distance $b = 2d$ have been obtained in the past by conformal transformation subject to the inequality $d \ll 2w$, where it is assumed that the thickness of the strip is small compared to the skin depth. In order to obtain a more accurate and comprehensive treatment, the integral equations for isolated and coupled strip antennas have been derived [1]. It is shown that the exact kernels of the integral equations for the current in a tubular antenna with length $2h$ and diameter $2a$ and for a strip antenna with length $2h$ and width $2w = 4a$ are identical. The integral equations for the two-element array and the N -element circular array of strip antennas are formulated. The equations are solved specifically for the closely spaced two-strip array, and the properties of the two-strip transmission line are obtained. The simpler cross-sectional geometry of coupled strip antennas with all currents confined to planes permits a more accurate

solution that takes account of the cross-sectional distribution of current in mutual as well as self terms. Thus, mutual coupling among strips can be evaluated more accurately than among tubular cylinders. A solution is obtained for the coupled integral equations for two parallel strips with equal and opposite total currents when so closely spaced that they constitute a strip line. Accurate general formulas are obtained for the line constants of the strip line. These are compared with the corresponding ones for the transmission line consisting of two tubular conductors.

In a separate study, the characteristic impedance and the complex wave number, together with the associated series impedance and shunt admittance per unit length, have been derived [2] for a horizontal wire with radius a or a strip with width $2w = 4a$ over a two-layered region. This consists of a layer of dielectric with thickness l over a conducting or dielectric half-space with large permittivity. The properties of the wire as an antenna or transmission line are determined from those of the insulated antenna with a two-layered eccentric insulation. The theory is extended to the strip conductor with the help of a comparison of the tubular and strip conductors over a perfectly conducting half-space.

Possible applications of the results include long wave antennas erected (a) on concrete or asphalt slabs over the earth, or (b) over swamps or shallow ponds, lakes or tidal basins. The theory also applies to horizontal dipole over any two-layered region. The analysis resembles that of open-wire transmission lines in that radiation into the air is neglected in the determination of the wave number and characteristic impedance and, therefore, of the current distribution. This is an excellent approximation when the conducting wire or strip is located at small electrical distances from the dielectric-coated half-space. Once the current distribution is known in terms of its dependence on the electrical properties of the several media involved, the electromagnetic field can be calculated from the known field of a unit horizontal dipole over a three-layered region.

Although the new theory of the strip transmission line does not apply directly to open microstrip transmission lines because the conducting strip is located above and not on the dielectric substrate, it is nevertheless closely related to the quasi-TEM approximations used in microstrip theory. In addition, the new theory includes the losses in the conducting strip, the dielectric substrate, and the conducting ground plane. Since they are due primarily to skin effect, they are frequency-dependent and this frequency dependence is properly contained in the formulas for the wave number and the characteristic impedance. It is significant, in this connection, that the losses in microstrip at frequencies above 40 GHz are primarily due to skin effect in the two conductors.

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1. R. W. P. King and T. T. Wu, "An Accurate Analysis of Coupled Strip Antennas and of the Strip Transmission Line," *Radio Science*, submitted for publication.
2. R. W. P. King, "Wire and Strip Conductors over a Dielectric-Coated Conducting or Dielectric Half-Space," *IEEE Trans. Microwave Theory & Tech.*, submitted for publication.

IV.8 Theoretical Study of Electromagnetic Pulses with a Slow Rate of Decay. T. T. Wu, R. W. P. King, J. M. Myers, and H. M. Shen, Contracts N00014-84-K-0465, Army LABCOM DAAL02-86-K-0095, and DOE Grant DE-FG02-84ER40158; Research Unit 11.

It has been shown recently [1] that the energy of an electromagnetic pulse, unlike that of a continuous electromagnetic wave, can decrease much more slowly than r^{-2} at large distances r . Such electromagnetic pulses are referred to as electromagnetic missiles.

For single-frequency continuous waves, the $O(r^{-2})$ dependence of the energy occurs only for large distances or low frequencies, i.e., $(ka^2/2r) \ll 1$, where k is the wave number and a is the aperture of the transmitter. On the other hand, it is well

known from Fresnel diffraction theory that, for short distances or high frequencies, i.e., $(ka^2/2r) \gg 1$, the decay of the energy with distance is other than r^{-2} . For a wide-spectrum electromagnetic pulse in which both of the above cases are involved, the nature of the energy decay was unclear. The concept of electromagnetic missiles [1] has provided extended insight into electromagnetic diffraction and energy decay in terms of the spectrum or the shape of the pulse.

Many practically interesting electromagnetic-missile sources—or electromagnetic-missile launchers—have already been analyzed. Some of these involve a current pulse distribution on a surface, for example, distributions on a circular disk or on a circular cylinder, i.e., at the end of an open circular waveguide [2]; or a Gaussian distribution on a plane [1]. Others involve a point source in certain reflecting or diffracting systems. The reflecting system can be a parabolic dish [3] or a spherical dish. The diffracting systems are dielectric lenses. Examples are the circular cylindrical lens [4], the spherical lens [5], and the prolate spheroidal lens. It now seems that electromagnetic missiles (and their scalar counterparts) are of very common occurrence when the excited pulse has a fast-rising shape. Much of this work is described in detail in the 1987 annual report prepared for the Army LABCOM [6].

It has also been found that whether a system has the ability to launch an electromagnetic missile or not depends on certain conditions, referred to as electromagnetic-missile criteria. These conditions can be expressed by means of optical ray tracing. The directional angle Ω of the ray arriving at the target is a function of the angle of emission Ω_0 at the source. In general terms the electromagnetic-missile criterion is equivalent to the vanishing of the Jacobian, viz., $(\partial\Omega/\partial\Omega_0) = 0$. After the application of this criterion to the dielectric spherical lens [5], it was found that there is a directly transmitted electromagnetic missile in the direction $\theta = 0$ under the condition $\nu = 1 + (a/b)$, where ν is the index of refraction of the sphere.

However, from the point of view of geometrical optics, there are many different rays—due to internal reflections—between the source point and the target point.

During the current reporting period, a general analysis has been carried out of the dielectric spherical lens [7], for the point source located either inside or outside the dielectric sphere. It is found that, like the directly transmitted radiation field investigated in [5], an internally multiply reflected radiation field can also become an electromagnetic missile under certain different electromagnetic-missile conditions. These conditions have been obtained and verified.

In a separate study, a rigorous analysis of the V-conical antenna has been completed [8]. This is an angular antenna that consists of a pair of infinitely long, triangular metal plates bent around a cone. The whole structure is identified by only two angles, the apex angle and the azimuth angle. The antenna is found to be frequency-independent, to emit a pure spherical wave even in the near region, and to have a directional field pattern. These characteristics make it very suitable as a feeding antenna in the electromagnetic-missile experiment, where an efficient and uniform illumination for a lens or reflector is needed.

Also during this period, the existence of electromagnetic missiles at off-axis field points and their properties have been examined theoretically, for the case when the launcher is a circular current disk. The results indicate that the electromagnetic-missile effect extends beyond the cylindrical region defined by the radius of the disk. Prior to this new evaluation, it was incorrectly believed that electromagnetic missiles exist only inside the cylindrical region. The transverse distribution of energy around the axis has been found to be stable, i.e., when the longitudinal distance increases, the transverse pattern of the energy remains the same. On the other hand, along the axis, the transverse energy pattern has a cusp. This is totally different from CW radiation, in which case the radiation pattern has a flat top on the axis of the main lobe. The subsequent derivation of the Poynting vector near the axis has confirmed

these results. The above properties of electromagnetic missiles will be investigated for other electromagnetic-missile launchers and their experimental verification will be sought.

So far, all of the wide variety of known electromagnetic missiles propagate in essentially straight lines. It is shown in a new paper [9] that an electromagnetic missile can follow a path that is strongly curved. Such curved missiles can be launched from a directed current density which has a uniform plane distribution in a bounded region. The difference from straight missiles is, however, that the orientation of the uniform current plane (as defined by the normal vector to the plane) varies with frequency. The results show that a significant fraction of the total radiated energy is contained in a sector or wedge-shaped region near the curved path. This sector has a small thickness in the direction of the current and a small angle in the direction of the rotated normal vector.

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3. J. M. Myers, "Pulsed Radiation from a Parabolic Reflector," presented at the SPIE O-E/LASE'88 Conference held in Los Angeles, CA, January 10-17 (1988); reprinted in *Microwave and Particle Beam Sources and Propagation*, Vol. 873, Proceedings of SPIE, 347-356 (1988).
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IV.9 Experimental Study of Electromagnetic Pulses with a Slow Rate of Decay. T. T. Wu, R. W. P. King, J. M. Myers, and H. M. Shen, Contracts N00014-84-K-0465 and Army LABCOM DAAL02-86-K-0095; Research Unit 11.

The purpose of the experiment is to demonstrate missile-like electromagnetic pulses. More specifically, this is a program to build and test devices capable of launching electromagnetic missiles. The program must measure the EMP accurately enough to confirm the slow decay of the energy and provide the means for improving the design of the EM-missile launcher. Because a missile-like electromagnetic pulse (EMP) involves transients with rise times under 100 ps, the measurement of short pulses is essential.

The experiment consists of an electromagnetic-missile launcher fed by a voltage pulse generator that radiates an EMP. The pulse travels above the ground plane, is received by an EMP sensor, and then recorded by a sampling oscilloscope. The platform is a 51×16 square-foot metal ground plane supported by a 4-foot-high wooden frame. The EM field is radiated, propagated, and received above the ground plane. Due to the image effect, the EM field above the ground plane is equivalent to that in free space.

Based on the theoretical analyses, several different EM-missile launchers have been designed. The first launcher is a parabolic dish fed by a point source at the focus. From the point of view of geometrical optics, an EM pulse with a spherical wave front is emitted from the focus, reflected by the dish, and becomes an EM

pulse with a plane-wave front. This EMP is expected to have EM-missile effects.

The second EM-missile launcher is an open circular waveguide. The radius of the tube is 2 feet. For high frequencies above 1 GHz, the asymptotic condition $ka \gg 1$ is satisfied, as required by the theory. The third launcher is a spherical lens with a point source either inside or outside the sphere. In order to reduce the weight, only a portion of the spherical shell is used. For any type of launcher, the entire structure consists of two parts: a feeder which emits a spherical wave, and a reflector or lens which reflects or refracts the spherical wave and transforms it into a plane wave.

It is crucial to have the exciting pulse as fast as possible. The pulse generator currently in use is a Picosecond Impulse Generator, Model 3500C, from Picosecond Pulse Labs., which has a rise time of 60 ps with an output of 8.5 V. This generator has been very stable. The recording sampling oscilloscope is a Tektronix Model 7854 Waveform Processing Oscilloscope. It combines the feature of wide bandwidth with digital storage. When the mainframe is integrated with a 7S11 Sampling Unit, S-4 Sampling Head, and 7B87 Time Base, it provides a rise time of up to 25 ps or a frequency bandwidth of 0-14 GHz for the EMP measurements.

Before starting the measurements, the system was tested to determine whether the cables, feeder, launcher, receiver and oscilloscope all behaved uniformly over the whole frequency range of the exciting pulse. The oscilloscope was found to acquire properly the voltage pulse directly from the generator without visible distortion. The cables and connectors are SMA series, which can handle high frequencies up to 18 GHz. The main difficulties were associated with the receiving sensor and feeding antenna. In order to assure that the measurements will be reliable, ways had to be found to detect an EM field over wide frequency bands with adequate sensitivity and to implement a point source for EM pulses with higher efficiency.

Several different types of receiving sensors were tested, including an electrically thin wire, a V-conical plate, and an asymptotic conical monopole. All of these probes have limited high-frequency responses. To solve this problem, a new type of EMP sensor—the L-antenna—has been designed, analyzed, and tested [1]. A comparison with the asymptotic conical dipole shows that the waveform detected by the L-antenna is significantly improved. By reducing the height h , the width of the pulse can be improved further. Although the shape of the waveform is very close to the original incident EMP, the signal picked up by the L-antenna is still very low. In order to improve the sensitivity while keeping the waveform free of distortion, a new V-antenna was designed and tested [1] which not only has a waveform that is closer to the original incident EMP, but its amplitude is much higher than that from the L-antenna. The L- and V-antennas have been analyzed approximately. They are simple, inexpensive and can detect the electromagnetic pulse with both high fidelity and sensitivity. They have the advantage that the waveform is obtained directly from the output *without integration*. In the experimental study of electromagnetic missiles, the pulse widths detected by these new sensors is only 6% wider than that of the incident EMP.

In order to emit an EM pulse with a spherical wave front, a special feeding antenna—the V-conical antenna—has been designed, analyzed and tested [2]. Such a V-conical antenna has the ability to emit a pure spherical wave. This is very important in order to obtain an “in phase” plane-wave front at the aperture of the dish. Other advantages include the fact that its structure is suitable for combining with a lens or reflector, and a theoretical analysis of its properties is feasible.

After adopting the newly designed transmitting antenna (V-conical antenna) and receiving antenna (L-antenna), the entire system was found to work properly up to 10 GHz. The first set of data has been reported [3]. The measurements were taken at 16 evenly spaced observation holes along the z -axis on the ground plane. The

EM pulse launcher was a parabolic dish. The recorded waveform is a complicated sequence of pulses rather than a single pulse. It consists of two subsequences, the first of which is emitted directly from the feeding antenna and the second is reflected by the parabolic dish. Of the five pulses contained in the secondary subsequence, the first two are expected to have a slowly decaying behavior. The manner in which the two pulse subsequences decrease with distance is found to be totally different. The primary pulse subsequence decreases according to $1/z$, while the secondary subsequence decreases much more slowly. Thus, it is seen that the energy of an EMP launched from an EM-missile launcher does have the property of slow decay.

Measurements were subsequently taken of the off-axis electromagnetic fields launched from the parabolic dish on the ground plane. The off-axis observation holes are located in the z direction at $z = 13, 25, 37$ and 49 feet. At each of these distances, there are five holes, with a 1-foot separation between them. The measured data show that (1) the energy decreases transversely beyond the cylindrical region defined by the radius of the parabolic dish, and (2) the transverse distribution of the energy is stable within $z = 37$ feet. Beyond this distance, the transverse distribution changes and spreads. An examination of the data indicates that the measured waveforms at different off-axis locations are comparable with those calculated from the theory.

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IV.10 Superdirective Properties of Closed Loops of Parallel Coplanar Dipoles. T. T. Wu, R. W. P. King, H.-M. Shen, B. H. Sandler, G. Fikioris, N. Filippopoulos, and D. K. Freeman, Contracts Air Force F19628-88-K-0024, N00014-84-K-0465, and Army LABCOM DAAL02-86-K-0095, and DOE Grant DE-FG02-84ER40158; Research Unit 11.

Antennas which transmit an extremely narrow beam are useful in point-to-point communication. Beams which are narrowed by transmission from apertures—as with horns and reflectors—are subject to diffraction and their field patterns have many minor lobes. Large broadside arrays of dipoles have similar characteristics. The usual design of endfire arrays can lead to negligible minor lobes but the main lobe is generally very broad. An exception is the superdirective or supergain antenna which has been investigated for endfire arrays of driven and parasitic elements. A quite different, very recently recognized possibility is the elliptical or egg-shaped closed loop of parallel parasitic elements excited by a single driven element at one end. When large enough with elements of proper length and correctly spaced, this array can resonate with a very high Q and narrow radiated beam. The resonant properties of a closed circular ring of parasitic elements have been observed, but the circular array does not have a narrow beam.

Antennas with very narrow beams have many important applications. For example, for communication by way of a satellite, highly directive antennas are important. If a closed-loop array with resonant superdirective properties can be designed, the amplitudes of the radiating currents will be limited by ohmic losses in the conductors. By taking advantage of superconductivity—which recent advances make possible at the temperature of liquid nitrogen—a supergain superconducting array could be developed for use in space where temperatures are nearly as low as that of liquid nitrogen. This may lead to a realization of the Einstein needlepoint radiation [1]–[3], which was known to be theoretically possible well over half a century ago, but for which no design has yet been successful.

The supergain theorem states that it is theoretically possible to design an antenna with arbitrarily small dimensions and a directivity as high as desired. It follows from a proof by Oseen [2] that the theorem is consistent with Maxwell's equations. The general consensus has been that superdirective antennas are impractical because of critical tolerances, narrow bandwidth, and very low efficiency. An exception to this point of view is found in the detailed investigation of Bloch, Medhurst and Pool [4] who state: "To dismiss superdirective aerials as impracticable merely because some inefficient superdirective current distributions have been found does not seem justifiable ... It appears that useful improvements in gain over conventional arrays can be obtained *without a prohibitive loss of bandwidth or efficiency.*"

The motivation to investigate further the resonant properties of large circular arrays of dipoles came from unrelated studies in quantum mechanics. Specifically, a recent paper by A. Grossmann and T. T. Wu [5] contains the following introductory sentences: "It is the purpose ... to study the quantum-mechanical analog of one of the most intriguing and practical phenomena in classical electromagnetism: the Yagi-Uda antenna array. Although invented over half a century ago and used almost universally for television reception, it has defied a complete theoretical analysis despite the many excellent papers on this topic." The paper goes on to study the quantum-mechanical analog, viz., an ideal polymer represented by an *infinite* one-dimensional array of equidistant point interactions (Fermi pseudopotentials). This is found to have resonances of zero width. A linear polymer of *finite* length does not have especially sharp resonances, due to radiation along its length. However, "a very narrow resonance should occur if the ideal polymer is bent into a closed loop ... The present investigation of the problem in quantum mechanics suggests strongly that similar extremely narrow resonances must occur in various antenna arrays. In particular, the circular array of dipole antennas must exhibit such a

resonance."

A further step in the study of narrow resonances in dipole arrays was taken by Wu [6] in an analysis of an array of the simplest, nontrivial scatterer in the context of Maxwell's equations, the pseudo-dipole. This is shown to have infinitely narrow resonances for the infinite array and "their existence is the underlying reason for the excellent properties of the finite array, including the Yagi-Uda array."

In order to investigate the possible and potentially important applications of an egg-shaped array as a superdirective microwave antenna, a systematic study must first be made of the properties of a circular array when the number of elements is large, one element is driven, and the dimensions are selected to lead to large resonances. The circular array must be analyzed first since, for it, the N simultaneous integral equations for the currents in and admittances of the elements can be replaced accurately by N independent integral equations for the N phase-sequence currents. However, in order to achieve extremely high directivity, a properly proportioned egg-shaped array will probably be required. This will have to be analyzed directly with only one element driven and not by a superposition of N phase sequences, each of which involves all elements driven. The validity of such a method will be verified with the circular array and then applied to the egg-shaped one.

Introductory aspects of the analysis of the circular array have been summarized in a paper scheduled for publication in February of 1989 [7]. The paper presents a review of available data from numerous experimental and theoretical researches—many carried out over 25 years ago—combined with the recent quantum-mechanical investigations [4], [5] mentioned above. The critical newly emphasized feature is the remarkable high- Q property of a correctly designed closed loop of coplanar dipoles when only one element is driven and all dimensions—the length of the elements, their cross-sectional size and shape, the number of elements, and the circumference of the closed loop—are correctly chosen. An immediate ap-

plication of the resonant circular array to beam scanning is described.

In order to analyze and design the resonant circular array more accurately, it is essential to find a simple but accurate method for solving the integral equation for the current in a single element, i.e., the tubular antenna. The three-term solution is simple and gives a rather good approximation of the current over the length of the antenna except near the open end. During this reporting period, the current and charge distributions near the end of a tubular antenna have been investigated using the Wiener-Hopf solution. The analysis shows that it is possible to derive an accurate asymptotic solution for the current and charge near the open end of a linear tubular antenna by means of the Wiener-Hopf technique. It is found that the solution is universal, i.e., that the relative distributions of charge per unit length and current within a distance of the order of the radius from the end are independent of the length of the antenna and of the frequency of operation. Two papers have been written on this subject. The first paper [8], which contains the mathematical details of the universal asymptotic solution, has been submitted for publication. The second paper [9], now in preparation, combines this universal solution for the current near the end of the antenna with the three-term solution for the other regions and compares the combination with experiments carried out 25 years ago [10].

A systematic study is in progress to improve the accuracy of the three-term theory [11] and simplify the evaluation of the several coefficients (Ψ functions) involved in the original formulation. The study has been completed for the single isolated dipole in a manner that eliminates the previously required special formula for the current in a half-wave dipole and provides simple integrated formulas for all coefficients. The interaction between two or more parallel dipoles is being investigated in detail for close and distant spacings and for driven and parasitic elements. The interaction is completely determined by the mutual vector potential which de-

depends on the distribution of current. Since this is quite different for center-driven and parasitic elements, the close coupling to such elements must also differ. It has been shown that a plane-wave formulation with appropriate radial distance factors is a good approximation even for quite close spacings, especially between parasitic elements. This should greatly simplify the accurate calculation of the mutual admittances among the many parasitic elements in a large array with only one driven element.

A study is in progress to determine the forward and backward gain of a circular array of point sources (pseudopotentials) in their dependence on the number N of elements, the spacing b of the elements, and the shape factor a . Preliminary results have been obtained for $N = 20, 50$ and 100 with wide ranges of both b and a , both for maximum conventional gain with all currents assigned and with only one element driven.

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**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

T. T. Wu, R. W. P. King, and H.-M. Shen, "Circular Cylindrical Lens as a Line-Source Electromagnetic-Missile Launcher," *IEEE Trans. Antennas Propagat.* (accepted). (Partial support from Army LABCOM Contract DAAL02-86-K-0095.)

R. W. P. King, "Supergain Antennas and the Yagi and Circular Arrays," *IEEE Trans. Antennas Propagat.* (accepted). (Partial support from Army LABCOM Contract DAAL02-86-K-0095 and Air Force Contract F19628-88-K-0024.)

H.-M. Shen, R. W. P. King, and T. T. Wu, "V-Conical Antenna," *IEEE Trans. Antennas Propagat.* (accepted). (Partial support from Army LABCOM Contract DAAL02-86-K-0095.)

R. W. P. King and T. T. Wu, "An Accurate Analysis of Coupled Strip Antennas and of the Strip Transmission Line," *Radio Science*.

R. W. P. King, "Wire and Strip Conductors over a Dielectric-Coated Conducting or Dielectric Half-Space," *IEEE Trans. Microwave Theory & Tech.*

J. M. Myers, H.-M. Shen, T. T. Wu, and H. E. Brandt, "Curved Electromagnetic Missiles," *J. Appl. Phys.* (Partial support from Army LABCOM Contract DAAL02-86-K-0095.)

H.-M. Shen, R. W. P. King, and T. T. Wu, "New Sensors for Measuring Very Short Electromagnetic Pulses," *IEEE Trans. Antennas Propagat.* (Partial support from Army LABCOM Contract DAAL02-86-K-0095.)

T. T. Wu and H.-M. Shen, "The Universal Current Distribution Near the End of a Tubular Antenna," *J. Math. Phys.* (Partial support from Army LABCOM Contract DAAL02-86-K-0095 and Air Force Contract F19628-88-K-0024.)

R. W. P. King, "Lateral Electromagnetic Waves from a Horizontal Antenna for Remote Sensing in the Ocean," *IEEE Trans. Antennas Propagat.*

b. Papers Published in Refereed Journals

T. T. Wu and R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on the Boundary Between Two Dielectrics," *J. Appl. Phys.* **62**, 4345-4355 (1987).

M. F. Brown, "Wave Packets of Lateral Waves Due to a Vertical Monopole: Experiment and Theory," *Radio Science* **22**, 833-846 (1987). (Partial support from ONR Contract N00014-79-C-0419.)

T. T. Wu, R. W. P. King, and H.-M. Shen, "The Spherical Lens as a Launcher of Electromagnetic Missiles," *J. Appl. Phys.* **62**, 4036-4040 (1987). (Partial support from Army LABCOM Contract DAAL02-86-K-0095.)

H.-M. Shen, T. T. Wu, and R. W. P. King, "Generalized Analysis of the Spherical Lens as a Launcher of Electromagnetic Missiles," *J. Appl. Phys.* **63**, 5647-5653 (1988). (Partial support from Army LABCOM Contract DAAL02-86-K-0095.)

R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on a Plane Boundary Between Dielectrics," *Journal of Electromagnetic Waves and Applications* **2**, 225-243 (1988).

R. W. P. King, "The Propagation of Signals Along a Three-Layered Region: Microstrip," *IEEE Trans. Microw. Theory & Tech.* **MTT-36**, 1080-1086 (1988). (Partial support from U.S. Army Research Office Contract DAAG29-84-K-0188 with Tufts University.)

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

R. W. P. King, "Lateral Electromagnetic Surface Waves and Pulses," presented at the Heinrich Hertz Symposium, held at the Universität Karlsruhe, FRG, March 14 and 15 (1988).

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

T. T. Wu and H.-M. Shen, "Radiation of an Electromagnetic Pulse from the Open End of a Circular Waveguide," presented at the SPIE O-E/LASE'88 Conference held in Los Angeles, CA, January 10-17 (1988); reprinted in *Microwave and Particle Beam Sources and Propagation*, Vol. 873, Proceedings of SPIE, 329-337 (1988).

J. M. Myers, "Pulsed Radiation from a Parabolic Reflector," presented at the SPIE O-E/LASE'88 Conference held in Los Angeles, CA, January 10-17 (1988); reprinted in *Microwave and Particle Beam Sources and Propagation*, Vol. 873, Proceedings of SPIE, 347-356 (1988).

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- j. **Graduate Students and Post-Doctorals Supported under the JSEP for the Year Ending 1 October 1988**

Dr. J. M. Myers, Mr. G. Fikioris, Mr. N. Filippopoulos.

V. SIGNIFICANT ACCOMPLISHMENTS REPORT

V.1 Multiphoton Vibrational Excitation of Molecules. E. Mazur, J. Wang, and K.-H. Chen; Research Unit 8, QUANTUM ELECTRONICS.

During the past three years, the experiments carried out under this contract have shown that the intramolecular vibrational energy distributions of infrared multiphoton excited molecules are not necessarily equilibrium ones. In particular, while an equilibrium distribution was observed for SF_6 [1], for CF_2Cl_2 the energy distribution was found to be highly nonthermal [2]. The quasicontinuum model, which is the generally accepted model for the description of infrared multiphoton excitation, is unable to explain the observed difference in behavior. During the past contract period we have modelled the infrared multiphoton excitation from the point of view of classical nonlinear dynamics, and found that certain resonance conditions can lead to rapid intramolecular equilibration.

To model the infrared multiphoton excitation we view the molecule as a collection of coupled nonlinear oscillators driven by external periodic forces [2,3]. One can then study the energy distribution of the system without knowing the solution of the equations of motion, much as is done in statistical mechanics. The question of interest is how the state of the molecule evolves from one with localized vibrational energy to one where energy is randomly distributed among all modes.

Although statistical mechanics works well for systems that have a large number of degrees of freedom, it does not apply to small isolated systems. It is well-known from classical mechanics that for a system with an integrable Hamiltonian, it is impossible for the system to become ergodic. For a system of many uncoupled oscillators, the phase space trajectory lies on a complex torus structure, which cannot

easily be visualized. Since only a small part of the total phase space allowed by energy conservation is occupied the system is not ergodic. The fundamental question therefore is now: how can such a system of many oscillators become ergodic?

In the early fifties Fermi, Pasta and Ulam performed a computer experiment, and showed that a small perturbation to an integrable Hamiltonian does not render the system ergodic [5]. Nearly at the same time Kolmogorov, Arnold and Moser proved a theorem, now referred to as the KAM theorem [6], which states that small nonintegrable perturbations can only distort, not destroy the phase space torus on which the trajectory of a system of nonlinear oscillators lies, except for those modes where the following resonance condition is fulfilled:

$$\sum_i n_i \nu_i = 0 \quad , \quad (1)$$

with ν_i the frequencies of the modes and n_i small integers. Both Fermi's experiment and the KAM theorem suggest that, in general, a system of nonlinear oscillators can only become ergodic when the energy involved is large enough, or when condition (1) is satisfied.

We have compared the number of resonances that satisfy condition (1) for SF_6 and CF_2Cl_2 with the infrared multiphoton excitation data for those molecules. In the Figure below, the vertical axis shows the number of times, N , that the following condition is satisfied,

$$\sum_i n_i \nu_i \leq 20 \text{ cm}^{-1} \quad . \quad (2)$$

Note that the n_i can be negative, otherwise Eq. (1) can never be satisfied. The 20 cm^{-1} on the right-hand side is chosen close to the total anharmonicity of a typical vibrational mode. Since our goal is to compare N for different molecules under the same condition, the value on the right-hand side is not critical. In the calculation, the set $\{n_i\}$ is permuted to cover all possible combinations, and the number of

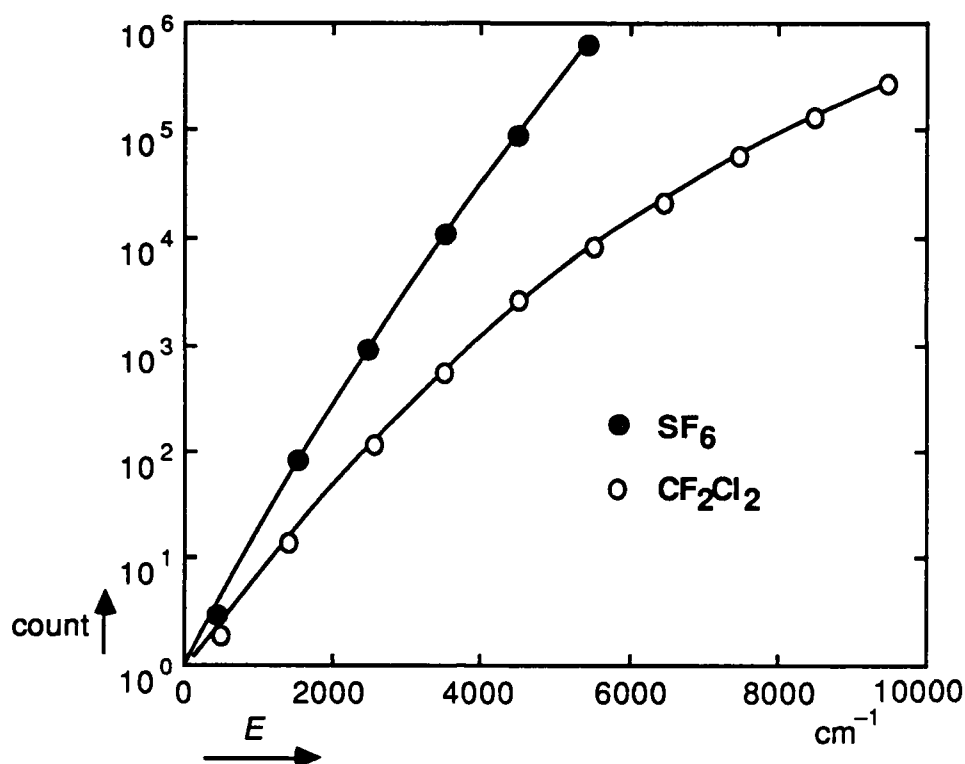


Figure 1. Number of incidences where Eq. (1) is satisfied as a function of excitation energy for SF_6 and CF_2Cl_2 . The number of incidences for SF_6 is one to two order of magnitude larger than that of CF_2Cl_2 . This suggests that SF_6 will behave ergodically at a much lower excitation energy than CF_2Cl_2 .

incidences is sorted according to the total internal energy of the molecule,

$$E = \sum_i |n_i| \nu_i \quad (3)$$

As one can see from Figure 1, N is orders of magnitude larger for SF_6 than for CF_2Cl_2 , and for both molecules N increases rapidly with energy. Also, the higher the excitation energy, the larger the difference between the two molecules. According to the KAM theorem this strongly suggests that SF_6 will behave ergodically at a much lower excitation energy than CF_2Cl_2 . Indeed, our previously reported experimental results [1,2] show that the intramolecular vibrational energy distribution of SF_6 after infrared multiphoton excitation is an equilibrium one, while the one of CF_2Cl_2 is not.

In conclusion, the KAM theorem can be applied to understand infrared multiphoton excitation and to provide insights on how nonresonant modes participate in the excitation process. In particular, our study shows that in addition to the density of states, which increases rapidly with the size of the molecule, condition (1) also plays an important role in determining the intramolecular energy distribution after infrared multiphoton excitation.

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V.2 Sensors for Pulses and for Detecting Submarines T. T. Wu, R. W. P. King, and H.-M. Shen; Research Unit 11, ELECTROMAGNETIC PHENOMENA.

Short electromagnetic pulses have many important applications. These include electromagnetic missiles that propagate in space with slow decay, pulses that travel along electromagnetic pulse (EMP) simulators for testing the hardness of aircraft and missiles against the EMP generated by a nuclear explosion in the atmosphere, and lateral-wave pulses that travel along the boundary between two different media such as air and earth, air and sea water, and sea water and the sea

floor. The detection, observation and measurement of an EMP requires an accurate sensor that correctly receives a pulsed signal and transmits it without distortion to a receiver. Experiments in conjunction with the study of electromagnetic missiles have shown [1] that conventional broadband sensors such as the asymptotic conical dipole are inaccurate and therefore inadequate. It has been shown [2], [3] that the conical sensor is, in fact, frequency-independent only over a band of frequencies near the resonant frequency of the cone. Very short pulses include a spectrum of frequencies that extends far beyond such a band. Sensors that receive short pulses with little or no distortion have been developed and tested [4] in conjunction with the generation and transmission of electromagnetic missiles. These are a correctly proportioned and oriented inverted L-antenna and V-antenna. They constitute a highly significant new contribution to pulse technology.

Recent extensive theoretical and experimental researches into the generation and propagation of lateral electromagnetic waves that travel along the boundary between air and sea have led to a significant improvement in an important application: remote sensing in the ocean with special reference to the detection of submerged submarines or mines. One method makes use of a long insulated transmitting antenna just below the surface of the ocean to generate a lateral-wave field that is scattered by the submarine or mine. This scattered field is observable by a receiver on the surface only when the electric field is parallel to the long dimension of the submarine and this is near resonance by proper selection of the frequency used. The weakness of this method is that the submarine can detect the incident field, align itself at right angles to the electric vector, and so reduce the scattered field to an unobservable magnitude and escape detection. The new development [5] eliminates this possibility by generating a circularly polarized lateral-wave field that maintains the same maximum amplitude at all orientations of the submarine. The complete theory and the quantitative technical requisites of this novel and po-

tentially very significant approach to the detection of submerged submarines and mines have been developed in detail.

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